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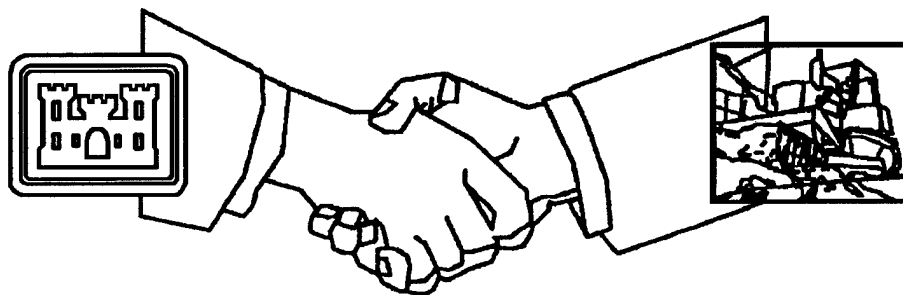Station

Final Report
CPAR-SL-95-2
December 1995

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Evaluation of Applications of DELVO Technology

by

Steven A. Ragan, Frank T. Gay

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**A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs**

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Evaluation of Applications of DELVO Technology

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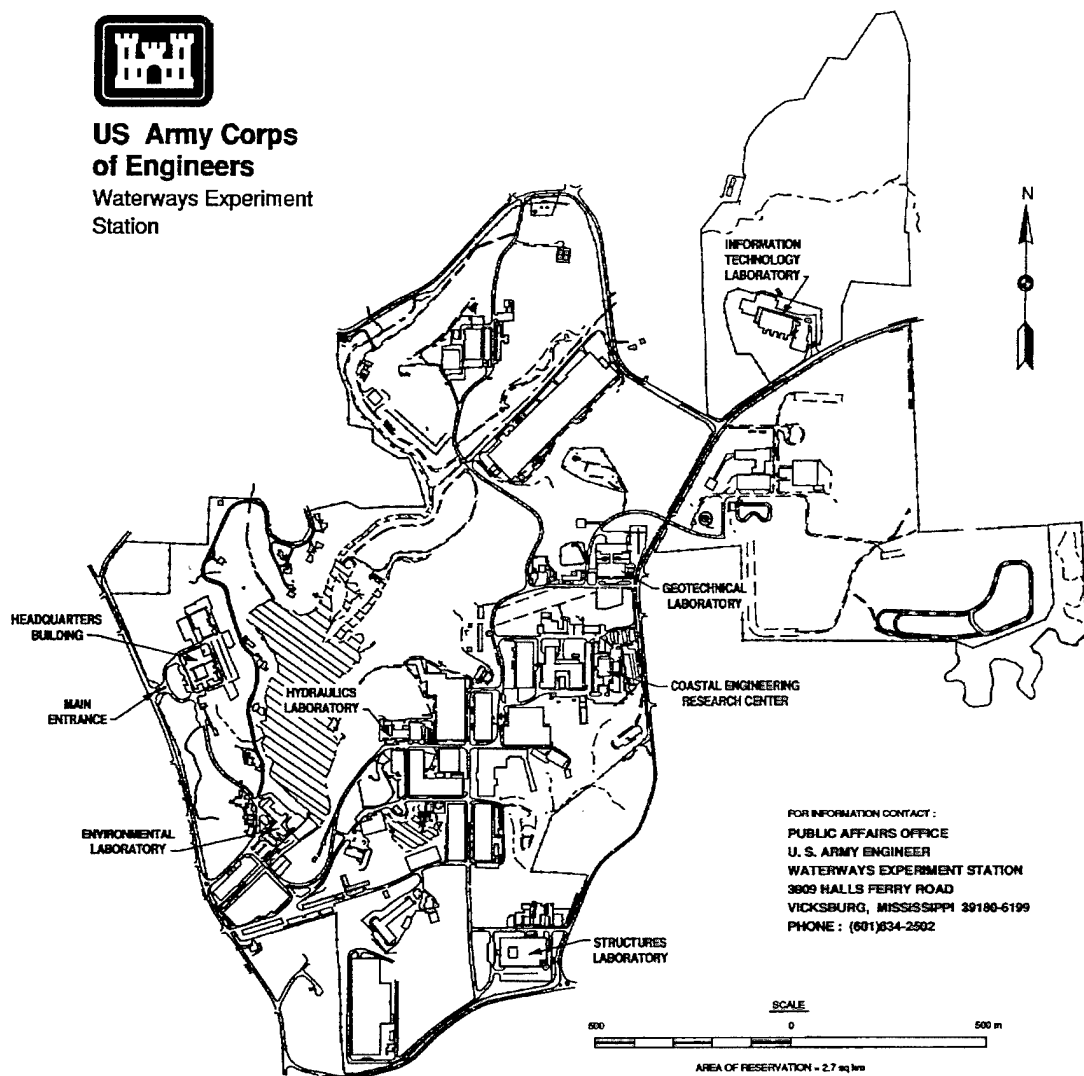23700 Chagrin Boulevard
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Final report

**US Army Corps
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STRUCTURES
LABORATORY

SCALE

500   0   500 m

AREA OF RESERVATION = 2.7 sq km

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Preface

construction. Mr. George Yoggy, Ms. Sandra Sprouts, Mr. Jeff Champa, Mr. Bert Czako, Mr. Cliff Strickland, Mr. Kevin Auerbach, and Mr. Steve Kovach, Master Builders, were very helpful in the gathering of data, practical information, and advice on DELVOCRETE and the use of DELVO Stabilizer in Shotcrete.

Messrs. Ragan, Bliss, and Ryan presented field demonstrations for this project. Messrs. Ryan and Bliss negotiated with local ready-mix concrete producers for the use of facilities and demonstrated the conventional applications of DELVO Stabilizer. They also made presentations to attending members of the U.S. Army Corps of Engineers on the various standard applications of DELVO Stabilizer. Mr. Buehner assisted in the development of the DELVO Stabilizer dose charts used in the testing at WES.

Reading and constructive criticism of this report were provided by Messrs. Mike Shydlowski, Greg Bobrowski, Godwin Amekuedi, Hamid Farzam, Ray Minnillo, Will Secre, and Bob Rayan, Master Builders.

At the time of preparation of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	metres
gallons (U.S. liquid)	3.785412	litres
inches	25.4	millimetres
ounces (U.S. fluid)	0.02957353	litres
pounds (force)	4.448222	newtons
pounds (force) per foot	14.5939	newtons per metre
pounds (force) per square inch	0.06894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per square foot	4.882428	kilograms per square metre
tons (2,000 pounds, mass)	907.1847	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9) (F - 32)$. To obtain kelvin (K) readings, use $K = (5/9) (F - 32) + 273.15$.

1 Introduction

Background

Fresh concrete is a perishable product that normally must be transported, placed, consolidated, and finished within a relatively short time if the hardened concrete is to develop the desired engineering properties and perform as intended. The American Society for Testing and Materials (ASTM) C 94 (ASTM 1993a) requires that concrete mixed by truck mixers be discharged within 1-1/2 hr or before 300 revolutions of the drum, whichever comes first, after the introduction of mixing water to the cement and aggregates or the introduction of the cement to the aggregates. These limitations can be waived only by the purchaser if the concrete is of such slump after the 1-1/2 hr or 300 revolutions that the concrete can be placed without the addition of water to the batch. The maximum time allowed for discharge may be reduced in hot weather. The U.S. Army Corps of Engineer (USACE) Guide Specification (CWGS-03301) for cast-in-place concrete (Headquarters, Department of the Army 1994) requires that concrete delivered to a work site by agitating equipment must be placed within 30 min after discharge into such equipment and that concrete delivered by truck mixer must be discharged within 1-1/2 hr after introduction of the cement to the aggregates. As a result of these concrete discharge time limitations, concrete producers often attempt to extend the concrete working time by introducing chemical admixtures into the concrete either at the time of batching or once the concrete has arrived on the work site. These admixtures may include retarding, water-reducing and retarding, or high-range water-reducing and retarding, or a combination of these which conform to ASTM C 494 (ASTM 1993b) Type B, D, or G, respectively. Although these admixtures are often effective for extending the working time of fresh concrete when the additional required working time is short, they are of limited use if the desired fresh concrete working time is several hours. In addition, when used near the maximum recommended dosages, they may retard the concrete time of setting to the extent that finishing operations and form removal are unnecessarily delayed.

In those cases where fresh concrete has exceeded the specified delivery times or when more concrete is ordered than can be used at a project, the producer must deal with disposing of it. Traditional methods of disposal

include dumping at the jobsite or in a landfill, discharging into a concrete reclaimer or recycling unit, producing highway barriers or other minor precast products, or constructing pads or bulkheads at the ready-mixed concrete plant. In addition, the concrete producer must also dispose of water used to wash truck-mixer drums unless it is reused as mixing water in accordance with ASTM C 94. Disposal of wash water is often accomplished by discharging it into a wash-water pit. Hardened concrete must then be periodically removed from the pit and properly disposed of.

Both waste fresh concrete and mixer wash water are classified by the Environmental Protection Agency (EPA) as hazardous waste (EPA 1992). The disposal of these materials is highly regulated by such legislation as the Resource Conservation and Recovery Act, the Water Quality Act, and the Superfund Amendments and Reauthorization Act. As a result, the availability of landfills authorized for disposal of waste fresh concrete and wash water will be significantly reduced in the future. The effect of these environmental regulations on concrete producers and users will likely be an increase in costs.

Research and development efforts by Master Builders, Inc., Cleveland, OH, have resulted in a commercially available admixture system, DELVO, which enables the concrete producer to tailor the working time of fresh concrete to that needed for particular applications and ambient conditions and to deal with the problems of waste fresh concrete and wash-water disposal. As has been stated, controlling the rate of portland-cement hydration with conventional retarders and accelerators is common practice. However, the ability to almost stop hydration for up to 72 hr and then activate the hydration process again so that a normal-setting, quality concrete is produced is novel. The DELVO admixture system consists of an unconventional retarding admixture, termed DELVO Stabilizer by Master Builders, Inc., and an accelerating admixture, termed DELVO Activator. The DELVO Stabilizer may be used to control hydration of the portland cement in a mixture for a prolonged period of time, such as may be necessary for long transportation distances. It may also be used to greatly slow cement hydration until such time that new concrete is added to it. At that time, the DELVO Activator may be added in order to counteract the effects of the DELVO Stabilizer and cause the entire batch of concrete to experience normal stiffening and setting. Research by Kinney (1989) indicates that the mechanism which allows the DELVO Stabilizer to almost stop hydration is explained most completely by how it affects the hydration of alite and the calcium aluminates, and the subsequent formation and growth of calcium silicate and aluminate hydrates. He states that the process can be thought of as forcing a metastable equilibrium on the system until such time as renewed reaction is desired or until the effect wears off and the cement spontaneously begins to hydrate.

Although the DELVO Stabilizer has been commercially available for several years, its novelty and perceived complicated character have limited the general acceptance of the product in the ready-mixed concrete industry. In addition, no thorough independent investigation of concrete containing the admixture had been conducted to confirm performance results reported by

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Master Builders, Inc. To address these questions and concerns, Master Builders and the U.S. Army Engineer Waterways Experiment Station (WES) entered into a Cooperative Research and Development Agreement (CRDA) under the Construction Productivity Advancement Research (CPAR) Program. The CPAR Program is a cost-shared research and development program aimed at assisting the U.S. construction industry in improving productivity by facilitating development and application of advanced technologies. As the productivity and competitiveness of the U.S. construction industry is advanced, savings will be realized for the Government, and the U.S. economy will be boosted. This document is the final report of the work undertaken under Fiscal Year 1990 CPAR Work Unit 32626.

Objectives

The objectives of this study were (a) to verify the performance test results reported by Master Builders for concrete containing the DELVO Stabilizer and Activator and (b) to develop new applications for DELVO technology in order to reduce concrete mixture costs, increase concrete construction productivity, and reduce the adverse environmental impact associated with the disposal of waste fresh concrete.

Scope

WES and Master Builders conducted separate investigations in order to meet the study objectives. WES focused attention on evaluating DELVO Stabilizer and Activator for standard ready-mixed concrete applications as defined by Master Builders, Inc. These applications included long-haul, same-day, and overnight stabilization. This investigation was patterned somewhat after the admixture evaluation procedures described in ASTM C 494 (1991i) in that control mixtures containing no DELVO Stabilizer were batched and tested along with those for each DELVO application. Tests conducted on the fresh and hardened concrete included temperature, slump, air content, time of setting, compressive strength, flexural strength, resistance to rapid freezing and thawing, length change, rapid chloride-ion penetration, and parameters of air-void system.

WES also investigated the feasibility of using DELVO Stabilizer to reduce peak temperatures in lean mass concrete and thereby minimize the cracking potential caused by the generation of excessive tensile stresses resulting from differential cooling within the structure. The concrete tested contained the same materials and had the same proportions as that proportioned and tested by WES in a thermal study for McAlpine Lock and Dam to be constructed on the Ohio River by the Louisville District, U.S. Army Corps of Engineers. Tests conducted included adiabatic temperature rise, shrinkage, creep, and static modulus of elasticity.

WES and Master Builders cooperated in an abbreviated investigation to assess the feasibility of using DELVO Stabilizer in roller-compacted concrete (RCC) for mass-concrete construction. This work focused on determining appropriate DELVO Stabilizer dosage rates for a typical RCC mixture so that it would remain in a fresh state for a prolonged period and then placing new RCC on top the following day with minimal joint cleanup and preparation. The bond strengths of lift joints within cylindrical test specimens, as measured by direct tensile and direct shear tests, were determined and compared to that of RCC lift joints which were prepared with bedding mortar.

A major focus for Master Builders in the study was the development of simplification procedures for generating DELVO Stabilizer dosage charts for the same-day stabilization application. A computer model based upon a database of field dosage data was developed and will enable Master Builders representatives to generate DELVO Stabilizer dosage charts for customers in a shorter period than was previously possible.

2 Investigation of Standard DELVO Applications

DELVO admixture technology was originally intended for overnight and weekend stabilization of returned fresh concrete and required the use of both the DELVO Stabilizer and Activator. With the addition of the appropriate dosage of DELVO Stabilizer, returned fresh concrete can be maintained in a fresh condition in the truck mixer or in a central holding container for 12 to 18 hr in the overnight stabilization application and for approximately 72 hr for the weekend stabilization application. The following day or after the weekend, the concrete is activated with the DELVO Activator and then combined with newly batched concrete and sent to the project site. Through its research, Master Builders has determined that a conventional accelerating admixture complying with ASTM C 494 (1993b) Type C will function satisfactorily as an activator. Both the overnight and weekend stabilization applications typically require that water along with the DELVO Stabilizer be added to returned fresh concrete. For overnight stabilization, water should be added to bring the slump to 4 to 6 in.[1] For weekend stabilization, water should be added until the slump is 6 to 9 in. Master Builders recommends adding the DELVO Stabilizer to the higher slump mixtures in order to help assure uniform distribution of the admixture. Of course, it is imperative that the concrete producer account for this added mixing water when batching the new concrete which is to be combined with the stabilized concrete. This is done by withholding the same quantity of water or more from the newly batched concrete as was added to stabilized concrete. Other than the reduction in mixing water, the proportions of the stabilized and newly batched concrete are the same. The ratio of newly batched concrete to stabilized concrete should be approximately 3 to 1 for both applications. Even at this ratio, the DELVO Activator or accelerating admixture is required in order for the combined concrete to experience normal times of setting.

The same-day stabilization of returned fresh concrete allows concrete producers to stabilize the concrete either immediately upon return to the plant so that new concrete may be batched on top of the stabilized concrete and

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[1] A table of factors for converting non-SI units of measurements to SI units is presented on page xiii.

immediately used, or to stabilize returned fresh concrete for a short period until the producer is able to locate a site where it may be used. When fresh concrete is returned to the concrete plant, water may need to be added to bring the concrete slump to approximately 4 to 6 in. DELVO Stabilizer is added, and then new concrete is batched either immediately or at some later time on top of the stabilized concrete. In most cases, the DELVO Activator is not needed for this application. As with the overnight stabilization application, any water added to the stabilized concrete must be deducted from the total mixing water added to the newly batched concrete.

Long-haul stabilization is used to control the rate of cement hydration for concrete that will be transported for long distances. Not only is the setting time retarded, but concrete stiffening is delayed. Knowing the transport time, the concrete producer adds the appropriate dosage of DELVO Stabilizer at the time concrete is initially batched. During the period of stabilization, the slump will be retained, and no temperature rise will occur. By the time the concrete arrives at the project site, the concrete begins to experience normal setting behavior so that finishing and form removal operations may proceed without unnecessary delay.

Other current commercial applications of the DELVO system include overnight and weekend stabilization of truck and central mixer wash water, same-day stabilization of concrete during truck breakdowns assuming the mixer drum can be turned to achieve sufficient mixing action, and same-day and overnight stabilization of leftover concrete from pumping operations.

The applications evaluated in this investigation included same-day stabilization of fresh concrete, overnight stabilization of fresh concrete, and a simulated long-haul application.

3 Materials, Mixtures, and Test Methods

Materials

Admixtures

Two 55-gal drums of the DELVO Stabilizer were received by WES from Master Builders in January 1992. The admixture was from lot no.16-3155-N2 and was later assigned WES Concrete Technology Division (CTD) serial no. 920347. Master Builders informed WES that the DELVO Stabilizer met the requirements of ASTM C 494 (ASTM 1991i) Type B when used at a dosage rate of approximately 4 fl oz/100 lb of cement. A subsequent evaluation by WES indicated that this assertion was correct. Summarized results of the WES ASTM C 494 (ASTM 1991i) evaluation of the admixture are shown on Table 1.

Table 1
Results of DELVO Evaluation as ASTM C 494 Retarding Admixture

Test	Test Results	Specified Requirements
Time of setting, allowable deviation from control, hr:min	Initial: + 1:57 Final: + 1:38	Initial: At least 1:00 later; not more than 3:00 later Final: Not more than 3:30 later
Compressive strength, minimum % of control	3 days: 107 7 days: 102 28 days: 101 6 months: 111 1 years: --[1]	3 days: 90 7 days: 90 28 days: 90 6 months: 90 1 years: 90
Flexural strength, minimum % of control	3 days: 117 7 days: 106 28 days: 101	3 days: 90 7 days: 90 28 days: 90
Length change, maximum shrinkage	0.005	0.010
Relative durability factor, minimum	104	80
[1] -- indicates no tests were conducted at this age.		

One 55-gal drum of Pozzutec 20 accelerating admixture was received from Master Builders in July 1992. It was from lot no. 127827N201 and was later assigned CTD serial no. 920348. Master Builders provided independent certification demonstrating that the admixture met ASTM C 494 (ASTM 1991i) Types C and E, but no testing was performed at WES to reverify this. The air-entraining admixture (AEA) was used in the investigation and was assigned CTD serial no. CL-60 AEA-1041. It is an aqueous solution containing surface-active agents consisting of fatty acids and salts of sulfonic acids. Testing conducted in a previous WES investigation indicated that this AEA met the requirements of ASTM C 260 (ASTM 1991f).

Cement and aggregates

Two ASTM C 150 (ASTM 1992c) Type I cements, from Lonestar Cement Co. and Capitol Cement Co., were used in this investigation to evaluate the effects of varying cement chemical and physical properties on DELVO Stabilizer dosage rates. These cements were assigned CTD serial nos. 920231 and 920232, respectively, and their properties are given in Table 2. No pozzolans or other cementitious materials were used in this investigation.

A natural siliceous sand, CTD serial no. 920024, was used as fine aggregate; and a crushed-limestone coarse aggregate, CTD serial no. 910018, was used in this investigation. Both the coarse and fine aggregate met the grading requirements of ASTM C 494 (ASTM 1991i), except the fine aggregate exceeded the maximum allowable limit of material passing the 300-μm (No. 50) sieve by 3 percent. The aggregate gradings, absorptions, and bulk specific gravities are given in Table 3.

Concrete Mixtures

Reference mixtures

Four reference mixtures were proportioned and evaluated using a number of fresh and hardened concrete tests. Each of the four mixtures was then evaluated in the laboratory under conditions that simulated same-day, overnight, and long-haul stabilization of fresh concrete to determine how the fresh and hardened properties changed. Two of the reference mixtures contained the Lonestar cement, and two contained Capitol cement. The respective cement contents of the Lonestar and Capitol mixtures were 517 and 658 lb/yd^3. Three replicates were made for each mixture, which resulted in a total production of 48 trial batches of concrete. Each mixture was proportioned to achieve a slump, as determined in accordance with ASTM C 143 (ASTM 1991b), of 3-1/2 $\pm$ 1/2 in., and an air content, as measured in accordance with ASTM C 231 (ASTM 1991e), of 6.0 $\pm$ 1.0 percent. The reference mixture proportions are given in Table 4.

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Table 2
Test Results for Type I Cements

Parameters	CTD No. 920231	CTD No. 920232
Chemical Determination		
SiO_2, percent	19.7	21.3
Al_2O_3, percent	5.1	4.2
Fe_2O_3, percent	2.0	2.7
CaO, percent	64.9	62.7
MgO, percent	1.4	3.8
SO_3, percent	3.3	2.9
Loss on ignition, percent	1.8	1.1
Insoluble residue, percent	0.17	0.15
Na_2O, percent	0.10	0.06
K_2O, percent	0.62	0.82
Alkalies-total as Na_2O, percent	0.51	0.60
TiO_2, percent	0.23	0.23
P_2O_5, percent	0.43	0.09
C_3A, percent	12	7
C_3S, percent	64	51
C_2S, percent	9	23
C_4AF, percent	6	8
Physical Tests		
Heat of hydration, 7-day, cal/g	--	--
Surface area, m^2/kg (air permeability)	377	350
Autoclave expansion, percent	0.00	0.09
Initial set, min. (Gillmore)	190	165
Final set, min. (Gillmore)	235	270
Air content, percent	8	9
Compressive strength, 3 days, psi	3,830	3,220
Compressive strength, 7 days, psi	5,080	4,140
False set (final penetration), percent	97	94

Table 3
Aggregate Test Results

Sieve Size	4.75 - 25.0 mm (CTD serial no. 910018)	75 - 4.75 mm (CTD serial no. 920024)
25.0 mm (1 in.)	100	
19.0 mm (3/4 in.)	96	
12.5 mm (1/2 in.)	54	
9.5 mm (3/8 in.)	29	
4.75 mm (No. 4)	5	100
2.36 mm (No. 8)	1	80
1.18 mm (No. 16)		68
600 μm (No. 30)		57
300 μm (No. 50)		23
150 μm (No. 100)		2
75 μm (No. 200)		0
Absorption, percent	0.3	0.8
Bulk specific gravity	2.76	2.60

Table 4
Reference Mixture Proportions

| Mixture | Saturated Surface-Dry Weights, lb/yd^3 | | | | | |
	Cement Brand	Portland Cement	Fine Aggregate	Coarse Aggregate	Water	Water to Cement Ratio (w/c)
DELREF1	LS[1]	517	1,225	1,958	237	0.46
DELREF2	Cap	517	1,206	1,927	256	0.49
DELREF3	LS	658	1,131	1,884	260	0.40
DELREF4	Cap	658	1,106	1,923	274	0.42

[1] LS = Lonestar Cement Co. and Cap = Capitol Cement Co.

Same-day stabilized mixtures

Each of the four reference mixtures was evaluated in the laboratory using general procedures recommended by Master Builders for same-day stabilization. The primary deviation from the Master Builders procedures was the batch size. Whereas full-scale batches are normally batched and mixed in truck mixers by Master Builders staff when assisting concrete producers in

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determining same-day DELVO Stabilizer dosage rates, this investigation simulated same-day stabilization using total batch sizes of 3.80 ft³. This was done so that multiple batches of concrete could be produced economically and in a timely manner with the aggregate, cements, and cement contents of interest. The DELVO Stabilizer dosage rate was determined by means of empirical procedures developed and recommended by Master Builders. These procedures typically included producing four to six 1.0-ft³ batches of each reference mixture and adding the DELVO Stabilizer to each at a varying dosage rate. The initial concrete temperature of each batch was measured, and the time of setting was monitored with a hand-held spring-reaction-type penetrometer until initial set as defined in ASTM C 403 (ASTM 1991g) was reached. Time zero for purposes of determining initial time of setting was defined as the time when the concrete reached 2.5-hr age, rather than the time it was initially discharged from the mixer. This simulated 2.5-hr-old concrete that might be returned to the concrete plant. The temperatures and initial times of setting of the stabilized batches were then compared to those of the reference mixtures with no DELVO Stabilizer. The dosages selected for use were those that retarded the time of initial setting, as defined above, approximately 2 hr beyond that of the reference mixtures.

Master Builders recommends that when returned fresh concrete is to be reused the same day, it should first be stabilized with DELVO; then approximately twice that volume of concrete having the same mixture proportions as the original batch should be added to it. Once same-day DELVO Stabilizer dosage rates were determined for the reference mixtures, the same-day stabilized trial batches were mixed in two stages to simulate reuse of returned concrete. First, 1.25 ft³ of a particular reference mixture was batched and mixed in accordance with mixing procedures described in ASTM C 192 (ASTM 1991d). The concrete remained in the mixer for 2-1/2 hr to simulate concrete that was sent out from a plant and then later returned. The mixer remained covered during this time to minimize evaporation of mixing water, and it was rotated 5 to 10 revolutions every 15 min to simulate agitation. DELVO Stabilizer was added to the batch at the end of the 2-1/2-hr aging period, and the concrete was remixed for 4 min. Then 2.55 ft³ of the same reference mixture was batched on top of the stabilized concrete, and the entire batch was again mixed in accordance with ASTM C 192 (ASTM 1991d). After completion of mixing, the batch was discharged from the mixer so that fresh concrete tests could be conducted and hardened concrete test specimens could be molded. The DELVO Stabilizer dosage rates for the same-day stabilized mixtures is given in Table 5.

Overnight stabilized mixtures

The four reference mixtures were also evaluated in the laboratory for overnight stabilization. The procedures followed in determining the DELVO Stabilizer dosage rates were similar to those used to determine the dosage rates for same-day stabilization. In accordance with recommendations by Master Builders staff, the Stabilizer dosages were determined for each

reference mixture such that time of initial setting was not achieved until approximately 30 to 36 hr after mixing. This would comfortably permit stabilization of the concrete for 12 to 20 hr, which is the typical duration of interest for ready-mixed concrete producers. The DELVO Stabilizer dosage rates for the overnight-stabilized mixtures is given in Table 5.

Table 5
DELVO Stabilizer Dosage Rates

| Reference Mixture | Stabilization, fl oz/100-lb cement | | |
	Same-Day	Overnight	Long-Haul
DELREF1	11	25	6
DELREF2	9	20	6
DELREF3	11	28	6
DELREF4	10	20	6

After dosage rates were determined for each reference, the overnight-stabilized mixtures were mixed in two stages to simulate concrete that was returned and then reused the following day. Following the same-day stabilization format, 1.25 ft³, of a particular reference mixture was batched and mixed in accordance with ASTM C 192 (ASTM 1991d). However, after the 2-1/2-hr aging period, water was added to the concrete to raise the slump to an estimated value of 8 to 10 in. The DELVO Stabilizer was then added, and the concrete was remixed for 7 min to ensure uniform distribution of the Stabilizer. The stabilized concrete was then discharged into a container and covered to prevent evaporation of mixing water. No additional agitation of the concrete occurred after discharge. Seventeen hours after addition of the DELVO Stabilizer, the concrete was prepared for reuse by returning it to the laboratory mixer and adding a predetermined dosage of Master Builders' Pozzutec 20, an ASTM C 494 (ASTM 1991i) Type C accelerating admixture. The concrete was then mixed continuously for 7 min, after which time 2.75 ft³ of concrete was batched onto the stabilized concrete. This concrete had proportions similar to those of the concrete originally batched, except water was withheld to compensate for that added during the stabilization process. The total trial batch was then mixed in accordance with ASTM C 192 (ASTM 1991d) and discharged so that fresh concrete tests could be performed and hardened concrete specimens could be molded. The DELVO Stabilizer dosage rates for the overnight-stabilized mixtures are given in Table 5.

Long-haul stabilized mixtures

Each long-haul stabilization mixture was produced by making a single batch of concrete and then adding the DELVO Stabilizer. Dosages were determined for the four reference mixtures such that after the addition of the

DELVO Stabilizer, the slump did not fall below the original concrete slump before 3-hr age. This would simulate a situation in which discharge of concrete from a truck mixer or agitator could be delayed by 3 hr without loss of workability or reduction in placing and finishing times. The DELVO Stabilizer dosage rates for the long-haul stabilized mixtures are given in Table 5. Each trial batch was 3.8 ft³ in volume and was mixed in accordance with ASTM C 192 (ASTM 1991d) before addition of the Stabilizer. After completion of this initial mixing, DELVO Stabilizer was added, and the concrete was remixed continuously for 4 min. The concrete was then held in the mixer for 3 hr and agitated every 15 min by revolving the mixer drum 5 to 10 revolutions. At the end of the 3-hr aging period, the concrete was discharged, fresh concrete tests were conducted, and hardened concrete test specimens were molded.

Elevated-temperature mixtures

Because much concrete placed in the United States today is placed at temperatures in excess of those maintained in the laboratory, an abbreviated study was performed to determine the effects of increasing the concrete temperature on low-cement content, same-day stabilized mixtures. Concrete materials were preconditioned in a 20- by 20-ft variable temperature room to 95° F for approximately 2 weeks prior to production of concrete trial batches. A 5-ft³ portable mixer was placed in the room with the materials so that mixing would occur at the elevated temperature. Reference mixture proportions were adjusted in order to maintain the slump and air content the same as for the laboratory-temperature concrete mixtures. However, the cement content of these mixtures was maintained at 517 lb/yd³. Each mixture was replicated three time for a total of 12 batches. Each batch had a total concrete volume of 3.8 ft³. The aging period of the first portion of the same-day mixture batches was reduced to 1-1/2 hr to account for the increased rate of slump loss at higher concrete temperatures. The elevated-temperature concrete mixture proportions are given in Table 6. The elevated-temperature reference mixtures were designated as DELREFH and same-day mixtures as DELSDYH.

Table 6
Elevated-Temperature Reference Mixture Proportions

	Saturated Surface-Dry Wt., lb/yd³					
Mixture	Portland Cement	Fine Aggregate	Coarse Aggregate	Water	w/c	DELVO Stabilizer, oz/100-lb cement
DELREFH-1	517	1,207	1,928	248	0.48	
DELREFH-2	517	1,190	1,905	270	0.52	
DELSDYH-1	517	1,214	1,940	248	0.49	14
DELSDYH-2	517	1,184	1,895	276	0.54	13

Test Methods

The conduct of fresh concrete tests and the preparation and testing of
hardened concrete test specimens followed standard procedures of ASTM.
The tests performed and applicable methods are given in Table 7. Test results
and discussion are given in Chapter 4.

Table 7 Summary of Test Methods	
Type Test	**Test Method or Specification**
Temperature of fresh concrete	ASTM C 1064 (ASTM 1991k)
Slump of fresh concrete	ASTM C 143 (ASTM 1991b)
Unit weight of fresh concrete	ASTM C 138 (ASTM 1991a)
Air content of fresh concrete	ASTM C 231 (ASTM 1991e)
Time of setting	ASTM C 403 (ASTM 1991g)
Compressive strength	ASTM C 39 (ASTM 1992a)
Flexural strength	ASTM C 78 (ASTM 1992b)
Freezing and thawing resistance	ASTM C 666 (Procedure A) (ASTM 1991j)
Drying shrinkage	ASTM C 157 (ASTM 1991c)
Chloride ion penetration	ASTM C 1202 (ASTM 1992k)
Static modulus of elasticity	ASTM C 469 (ASTM 1992g)
Parameters of air-void system	ASTM C 457 (ASTM 1991h)

Temperature

The temperature of fresh concrete is an important factor in determining and
evaluating the correct dosage of DELVO Stabilizer for each application.
Therefore, fresh concrete temperature measurements were made according
with ASTM C 1064 (ASTM 1991k) on all batches in order to verify that the
proper DELVO Stabilizer dosage had been used.

Slump, unit weight, and air content

Slump tests were performed in accordance with ASTM C 143 (ASTM
1991b) on samples from concrete both before and after the addition of the
DELVO Stabilizer for the overnight and long-haul stabilized mixtures. Slump
tests were performed on the same-day stabilized mixtures only after the
Stabilizer was added. Unit weight, pressure-method air content tests were
conducted according to ASTM C 138 (ASTM 1991a) and C 231(ASTM
1991e), respectively, on samples from all trial batches after the addition of the
Stabilizer.

Time of setting

Since a primary function of DELVO Stabilizer is to extend the time of setting of concrete for various applications, actual knowledge of the concrete time of setting was critical. Time-of-setting tests were conducted according with ASTM C 403 (ASTM 1992g) on all batches after addition of the DELVO Stabilizer. For purposes of comparing the times of setting of the reference mixtures with those of the stabilized mixtures, zero time was taken as the time the DELVO Stabilizer and new concrete, as applicable, were added to the aged concrete.

Compressive strength

The unconfined compressive strengths of specimens representing the replicate batches of each mixture were determined according to ASTM C 39 (ASTM 1992a). Six 6- by 12-in. cylinders were molded from each batch, and one each was tested at 3-, 7-, 14-, and 28-days; and 6-months; and 1-year age.

Static modulus of elasticity

Each 6- by 12-in. cylinder tested for compressive strength at 28-days age was also strain-gaged so that vertical strains could be measured and the chord modulus of elasticity determined according to ASTM C 469 (ASTM 1992g).

Flexural strength

The flexural strengths of specimens representing the replicate batches of each mixture were determined according to ASTM C 78 (ASTM 1992b). Three 6- by 6- by 21-in. beams were cast from each batch, and one each was tested at 3-, 7-, and 28-days age.

Resistance to rapid freezing and thawing

The resistance to deterioration resulting from cycles of rapid freezing and thawing was determined according to ASTM C 666 (ASTM 1991j) (Procedure A). One 3-1/2- by 4-1/2- by 16-in. beam was molded from each batch of concrete and cured in lime-saturated water at 73° F for 14 days prior to the initiation of freezing and thawing. All specimens were subjected to 300 cycles of freezing and thawing. Values of relative dynamic modulus-of-elasticity calculated from resonant flexural frequency measurements were used to monitor the deterioration of the test specimens during progression of the cycles, and the durability factor of each was calculated at the conclusion of testing in accordance with ASTM C 666 (ASTM 1991j).

Length change

One beam measuring 3- by 3- by 10-in. was molded from each batch in accordance with ASTM C 157 (ASTM 1991c). Each beam was demolded after 24 hr, and an initial comparator reading was taken. Beams were then stored for 28 days in lime-saturated water at 73° F and then for a period of 28 days in air at 50-percent relative humidity and 73° F.

Resistance to chloride-ion penetration

The permeability of a specimen representing each batch was estimated following the ASTM C 1202 (ASTM 1992k) test method. In this test, the chloride-ion penetrability is determined on a preconditioned specimen by measuring the number of coulombs that can pass through a sample in 6 hr. One 4- by 8-in. cylinder was molded from each batch and moist cured for 28 days. A 2-in.-long sample was then sawed from the top of the cylinder and used as the test specimen.

Parameters of air-void system

A sample was sawed from one freezing-and-thawing test beam representing each mixture after completion of testing. The parameters of the air-void system of each sample were determined according to ASTM C 457 (ASTM 1991h). These parameters included paste volume, entrained air content, entrapped air content, total air content, and spacing factor.

4 Test Results and Discussion

Fresh Concrete Tests—Laboratory Temperature

Individual test results for temperature, slump, unit weight, and air content are given in Table A1, Appendix A1. Table 8 provides a summary of the average of the individual fresh concrete test results. The summarized data are grouped by mixture cement type and content so that relative comparisons may be made between applications. Mixture designations are DELREF, DELSDY, DELOVN, and DELLHL, which represent reference mixtures and same-day-, overnight-, and long-haul-stabilized mixtures, respectively. For overnight-stabilized mixtures, fresh tests were conducted on samples before the addition of DELVO Stabilizer and on samples taken 18 hr after the Stabilizer addition. For example, DELOVN-1A represents the mixture before addition of DELVO Stabilizer, and DELOVN-1B represents the batch after the addition of DELVO Stabilizer and after new concrete has been batched onto the stabilized concrete. In the case of long-haul-stabilized mixtures, fresh concrete tests were performed on samples before the addition of DELVO Stabilizer, immediately after addition of the Stabilizer, and after the stabilized, fresh concrete was 3-hr age. Table 8 reflects this by showing average test results for DELLHL mixtures labeled "A," "B," and "C," respectively.

The fresh concrete test results summary indicates that regardless of the application selected, properties comparable to those of the original reference mixture were achieved. This is noteworthy, particularly in the case of the overnight-stabilized mixtures, because both chemical admixtures and new concrete were batched and mixed with existing concrete which had experienced considerable aging. Those mixtures stabilized with DELVO Stabilizer for the long-haul application did experience some loss of slump with time, but the slump at 3-hr age was generally only slightly less than that of concrete before it was stabilized. The long-haul mixtures labeled as "B" generally had both slumps and air contents greater than the prestabilized samples, indicating that the DELVO Stabilizer has both water-reducing and air-entraining capabilities which should be considered during development of mixture proportions.

Table 8
Summary of Fresh Concrete Test Results (Laboratory-Temperature Concrete)

Mixture	Concrete Temperature, °F	Slump, in.	Unit Wt, lb/ft³	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELREF-1	77	3-1/2	145.2	5.9	3:45	5:20
DELSDY-1	76	3-1/2	144.9	6.2	4:26	5:36
DELOVN-1A	75	4	143.5	7.7	--[1]	--
1B	76	3-1/2	145.3	6.4	3:56	5:23
DELLHL-1A	70	2-3/4	--	--	--	--
1B	71	4	144.4	6.6	--	--
1C	68	2-1/4	145.9	5.8	7:53	9:43
DELREF-2	76	3-1/4	144.3	5.8	4:46	6:35
DELSDY-2	74	4	143.6	5.9	5:23	7:22
DELOVN-2A	74	4	144.1	6.3	--	--
2B	74	3-1/4	144.1	6.5	4:23	6:05
DELLHL-2A	66	3	--	--	--	--
2B	64	4-1/2	143.2	6.4	--	--
2C	63	2-3/4	143.8	6.1	8:47	10:43
DELREF-3	76	3-1/2	145.3	5.9	4:12	5:37
DELSDY-3	75	3-1/4	145.2	6.0	4:15	5:50
DELOVN-3A	76	3-1/2	145.2	6.4	--	--
3B	76	4-1/2	146.5	5.7	4:48	6:15
DELLHL-3A	66	3-1/4	147.3	4.2	--	--
3B	66	5	144.0	6.6	--	--
3C	66	3-1/2	144.3	6.4	7:57	9:10
DELREF-4	77	3-3/4	142.1	6.1	4:05	5:42
DELSDY-4	76	3-1/4	144.0	5.8	4:20	6:01
DELOVN-4A	67	3-1/2	143.1	7.0	--	--
4B	76	3-1/2	145.3	5.5	4:50	6:11
DELLHL-4A	67	3-3/4	145.3	4.7	--	--
4B	67	5	142.9	6.1	--	--
4C	68	3	144.0	5.7	9:24	10:49

[1] -- indicates this test was not conducted on this mixture.

The initial and final times of setting the same-day- and overnight-stabilized mixtures were measured from the time that new concrete was batched on top of the aged, fresh concrete. The summary of time of setting results in Table 8 shows that both the initial and final times of setting are within 45 min of the times of setting for the respective reference mixtures. This indicates that although the procedure followed for establishing DELVO Stabilizer dosage rates was empirical, it enabled effective control of concrete times of setting for these applications. The initial and final times of setting of the long-haul-stabilized mixtures were measured from the time concrete was initially batched. The times of setting for these mixtures are 3 to 5 hr longer than the respective reference mixtures, indicating that the DELVO can be used, within reasonable limits, to effectively control time of setting of fresh concrete.

Fresh Concrete Tests—Elevated Temperature

Only the low-cement content reference and same-day stabilization mixtures were evaluated at a nominal concrete temperature of 95 °F. Individual test results for temperature, slump, unit weight, air content, and time of setting are given in Table A2, Appendix A. Table 9 gives a summary of the average of the individual fresh concrete test results. These results indicate that, even at an elevated concrete temperature, DELVO Stabilizer can be used to produce same-day stabilized concrete which has fresh properties very comparable to those of the respective reference mixtures.

Table 9 Summary of Fresh Concrete Test Results (Elevated-Temperature Concrete)						
Mixture	Concrete Temperature, °F	Slump, in.	Unit Wt, lb/ft³	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELREFH-1	94	3-3/4	144.0	6.5	4:02	5:28
DELSDYH-1	94	3	145.7	5.8	3:57	5:11
DELREFH-2	97	3-1/2	143.9	5.9	4:47	6:44
DELSDYH-2	96	3-1/2	143.2	6.2	4:46	6:16

Hardened Concrete Tests—Laboratory Temperature

Compressive strength

Five 6- by 12-in. cylindrical compressive-strength test specimens were molded from each batch of concrete. Specimens were molded only from the final batch after all admixtures and new concrete, as applicable, were batched

and mixed. One specimen each was tested for compressive strength at 1-, 3-, 7-, and 28-days age, and at 6-months age. A pair of resistance strain gages was also mounted in the vertical direction on each of the 28-day specimens so that vertical strains could be measured and the chord modulus of elasticity calculated. Individual compressive-strength tests results and modulus-of-elasticity values are given in Table B1, Appendix B. Averages of the individual compressive-strength test results and the modulus values are given in Table 10. Within each of the four mixtures evaluated, each stabilization application resulted in compressive strengths comparable to the reference mixture. This is illustrated in Figures 1-4, in which the strengths of the stabilization mixtures at each age are plotted relative to the respective reference mixtures. These figures show that, for all ages tested, the compressive strengths for all applications were not less than 90 percent of those of the reference mixtures. In particular, the overnight- and long-haul-stabilized-mixtures had compressive strengths greater than 100 percent of

Table 10
Summary of Compressive-Strength and Modulus-of-Elasticity Tests Results
(Laboratory-Temperature Concrete)

| Mixture | Average Compressive Strength, psi | | | | | 28-day Static Modulus of Elasticity, 10^6 psi |
	1-day	3-day	7-day	28-day	6-month	
DELREF-1	1,717	2,520	3,250	4,220	4,960	5.18
DELSDY-1	1,620	2,487	3,140	4,230	5,233	5.47
DELOVN-1	1,837	2,890	3,820	4,203	5,567	4.82
DELLHL-1	1,693	2,770	3,407	4,250	5,187	5.63
DELREF-2	1,836	2,903	3,533	4,247	4,963	5.14
DELSDY-2	1,687	2,630	3,493	4,370	4,810	5.24
DELOVN-2	2,160	3,237	3,927	4,653	5,213	5.02
DELLHL-2	2,123	3,263	3,980	4,793	5,240	5.43
DELREF-3	2,323	3,113	3,720	4,187	5,713	5.21
DELSDY-3	2,117	2,913	3,390	4,420	5,423	5.31
DELOVN-3	2,610	3,900	4,290	5,437	6,230	5.45
DELLHL-3	2,097	3,023	3,680	4,467	5,723	5.57
DELREF-4	2,007	2,977	3,690	4,620	5,390	4.96
DELSDY-4	2,277	3,373	3,947	4,650	5,610	5.09
DELOVN-4	2,710	4,057	4,720	5,163	6,417	5.40
DELLHL-4	2,340	3,400	4,087	4,730	5,740	5.43

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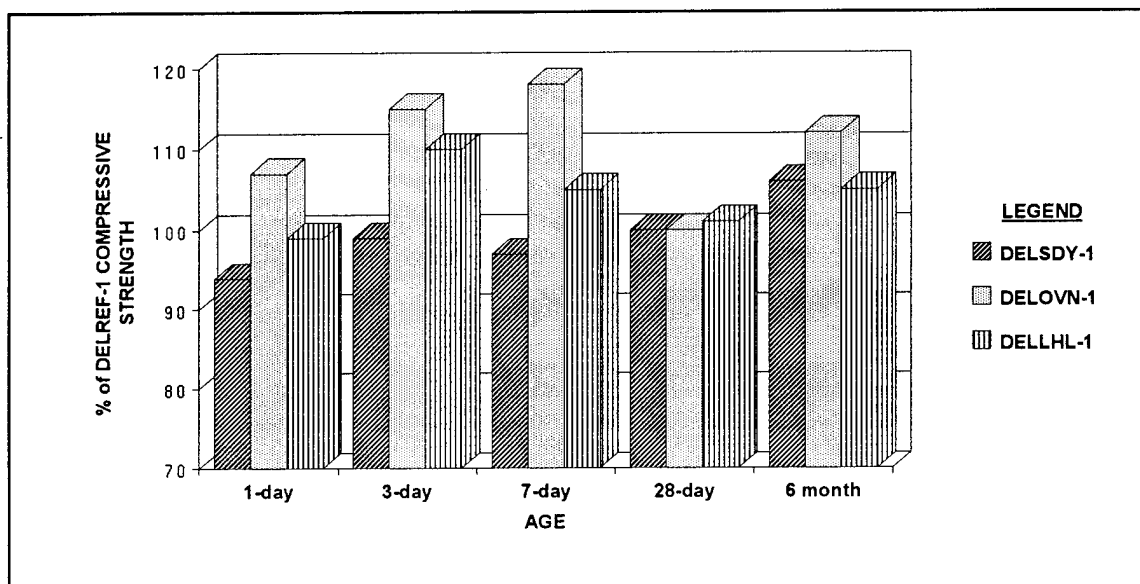
Figure 1.   Relative compressive-strength comparison between stabilized mixtures and reference mixture DELREF-1
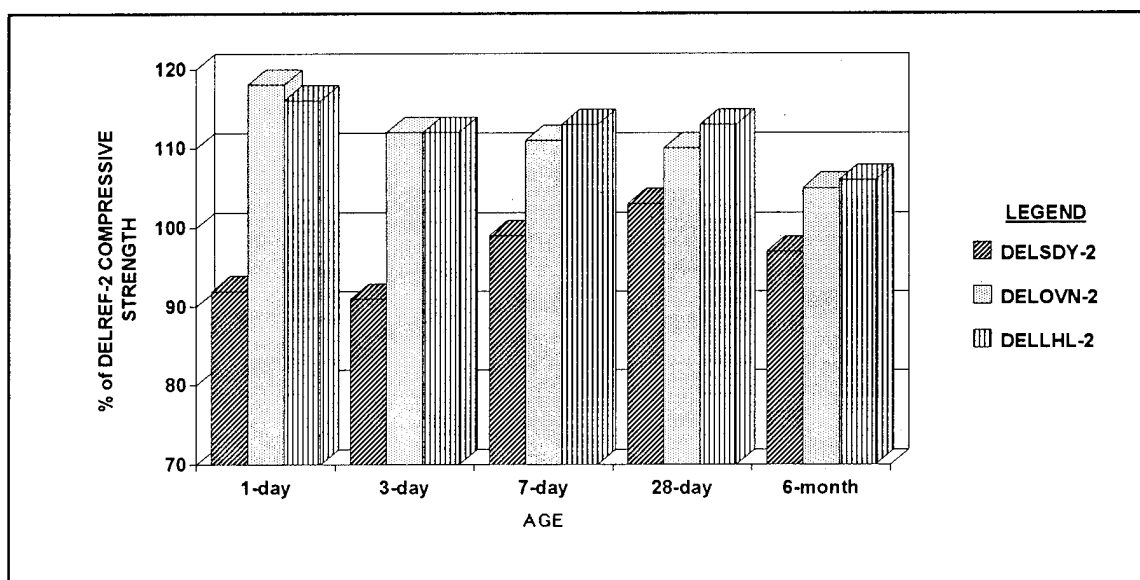
Figure 2.   Relative compressive-strength comparison between stabilized mixtures and reference mixture DELREF-2
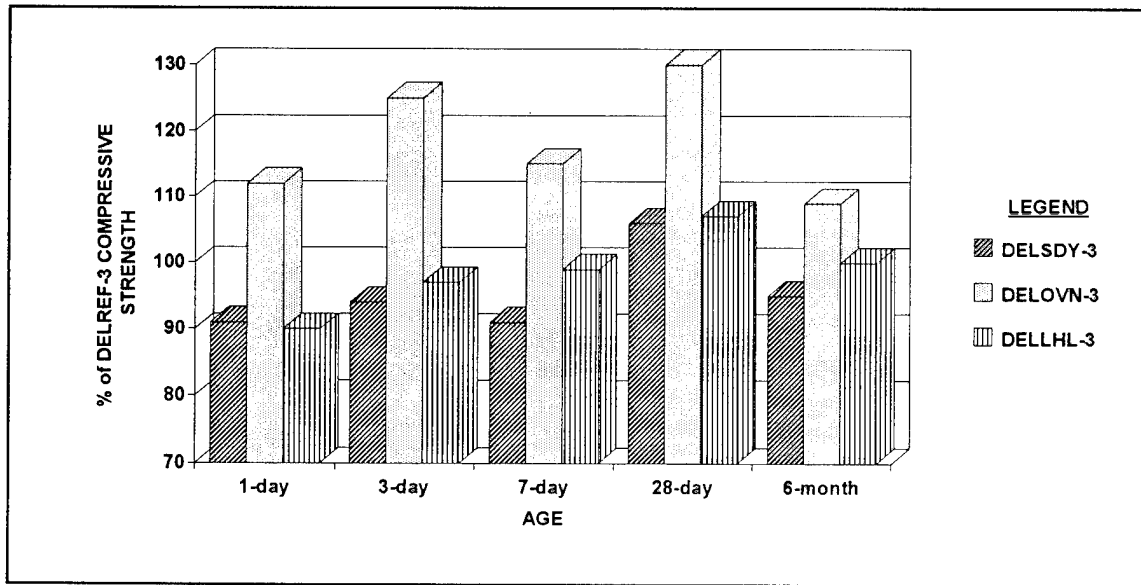
Figure 3. Relative compressive-strength comparison between stabilized mixtures and reference mixture DELREF-3
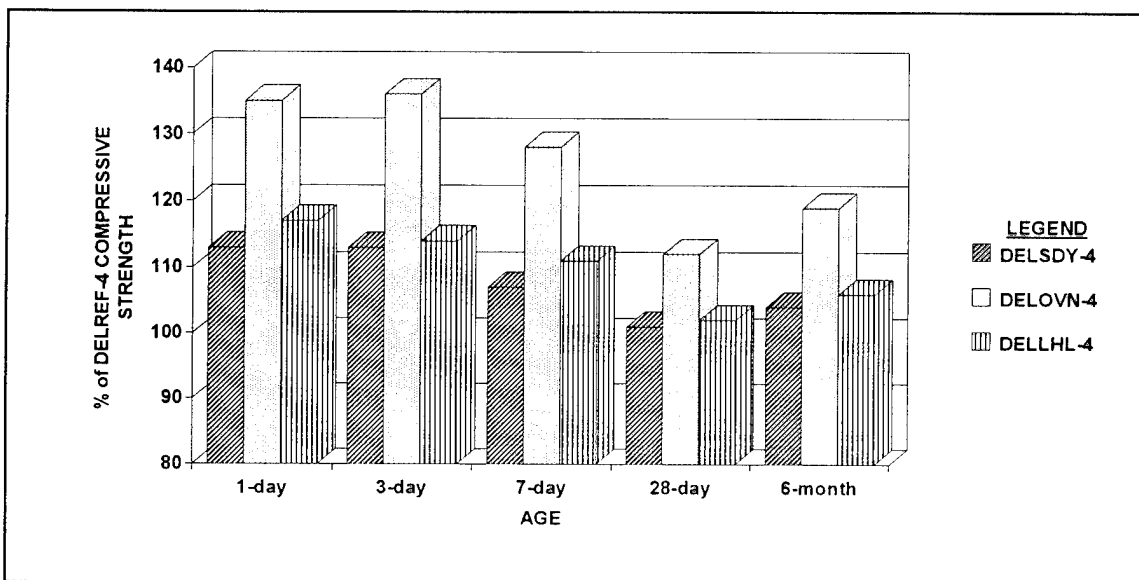
Figure 4. Relative compressive-strength comparison between stabilized mixtures and reference mixture DELREF-4

those of the reference mixtures for almost all ages tested. The same-day-stabilized mixtures had compressive strengths equal to or slightly less than those of the reference mixtures, particularly at the earlier ages. Since the total water contents in the stabilized mixtures were the same as those used in the respective reference mixtures, differences in compressive strength cannot be attributed to differences in w/c ratio. In addition, strength differences cannot be attributed to variations in air contents since they were comparable for all mixtures. Some strength increase in the stabilized mixtures may be due to favorable modification of the cement hydration reaction and paste microstructure.

The coefficients of variation of the within-mixture 28-day compressive strength and moduli of elasticity given in Table 7 are less than 7 percent, except for mixture 3. This mixture had a 28-day compressive-strength coefficient of variation of 12 percent. Therefore, the use of DELVO appears to have little significant effect on the modulus of elasticity, regardless of stabilization application.

Flexural strength

Three beam specimens were molded from each batch after all admixtures and new concrete, as applicable, were batched and mixed. Beams were tested to determine flexural strength using third-point loading at 3-, 7-, and 28-days age. Individual flexural strength test results are given in Table B2, Appendix B. Averages of the individual flexural strength test results are summarized in Table 11. Again, the data are grouped by mixture cement type and content for comparison purposes. Figures 5-8 show that, like the compressive strengths, the average flexural strengths of the stabilized mixtures are generally at least 90 percent of those of the reference mixtures. The average flexural strengths of the overnight-stabilized mixtures exceeded those of all reference mixtures at all ages except DELREF-2. The 3- and 7-days age strengths of the same-day- and long-haul-stabilized mixtures were generally less than those of the reference mixtures, but the 28-day strengths were equal to or exceeded those of the reference mixtures.

Resistance to rapid freezing and thawing

One prism was molded from each batch after all admixtures and new concrete, as applicable, were batched and mixed. The prisms were demolded at 24-hr age and continuously cured in lime-saturated water until 14-days age. They were then tested for resistance to cycles of rapid freezing and thawing by calculating the relative dynamic modulus of elasticity from flexural resonant frequency until 300 cycles of freezing and thawing were achieved. A complete cycle of freezing and thawing occurred every 2 hr as specimens were alternatively lowered to 0° F and then raised to 40° F. The durability factor of each specimen was calculated as described in ASTM C 666 (ASTM 1991j). Individual durability factors are given in Table B3, Appendix B. The

Table 11
Summary of Flexural-Strength Test Results (Laboratory-Temperature)

Mixture	Average Flexural Strength, psi		
	3-day	7-day	28-day
DELREF-1	480	625	717
DELSDY-1	475	560	753
DELOVN-1	563	665	782
DELLHL-1	465	633	737
DELREF-2	575	628	683
DELSDY-2	540	658	703
DELOVN-2	557	650	662
DELLHL-2	613	685	693
DELREF-3	608	670	761
DELSDY-3	560	628	717
DELOVN-3	718	787	908
DELLHL-3	540	718	830
DELREF-4	573	657	700
DELSDY-4	655	730	753
DELOVN-4	717	757	820
DELLHL-4	676	748	777
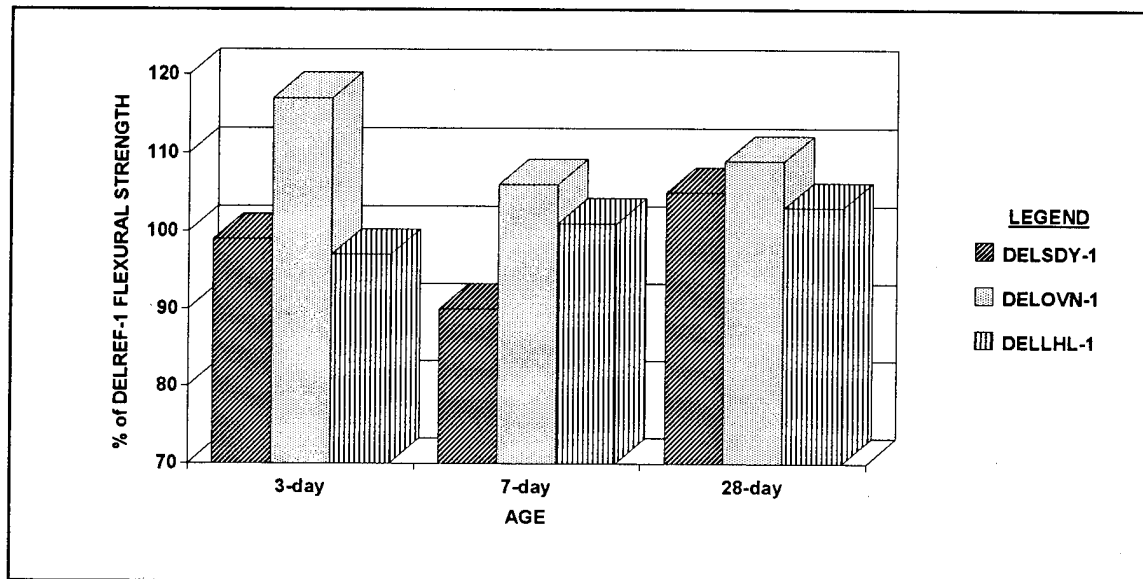
Figure 5.   Relative flexural-strength comparison between stabilized mixtures and reference mixture DELREF-1
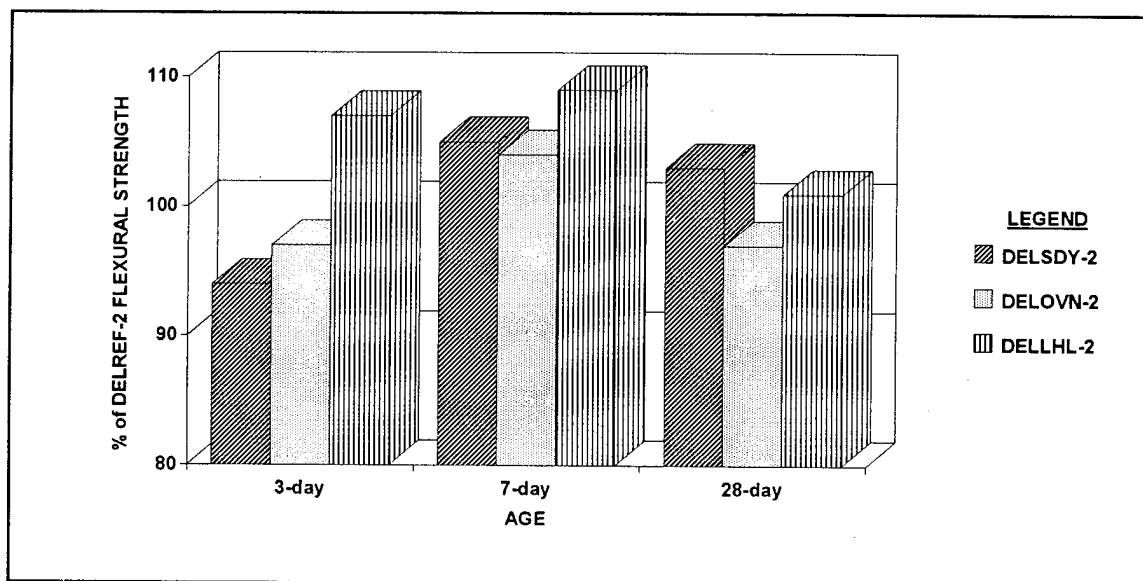
Figure 6.   Relative flexural-strength comparison between stabilized mixtures and reference mixture DELREF-2
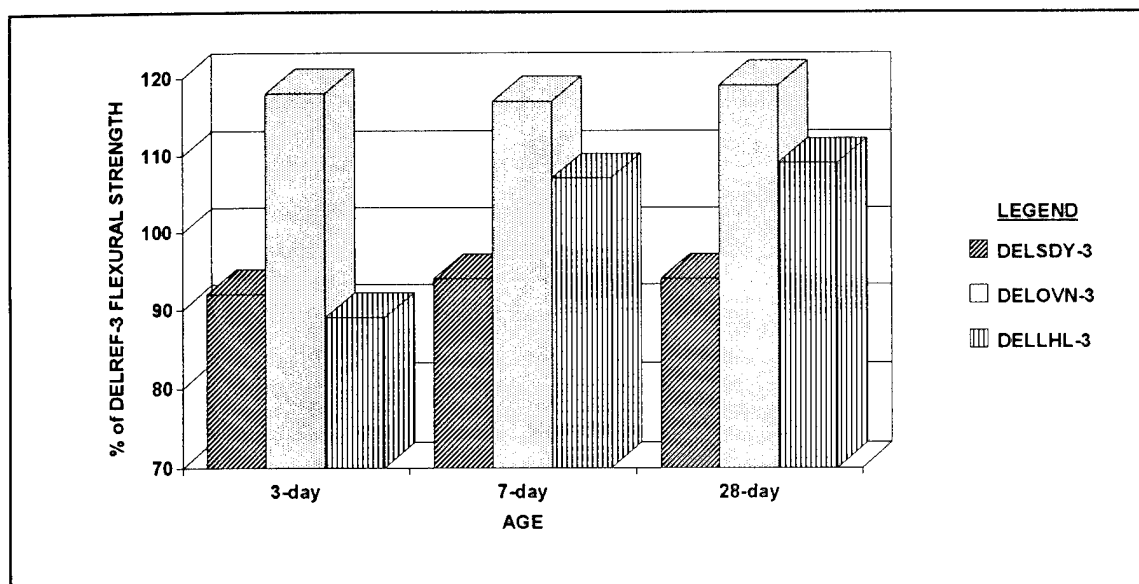
Figure 7.   Relative flexural-strength comparison between stabilized mixtures and reference mixture DELREF-3
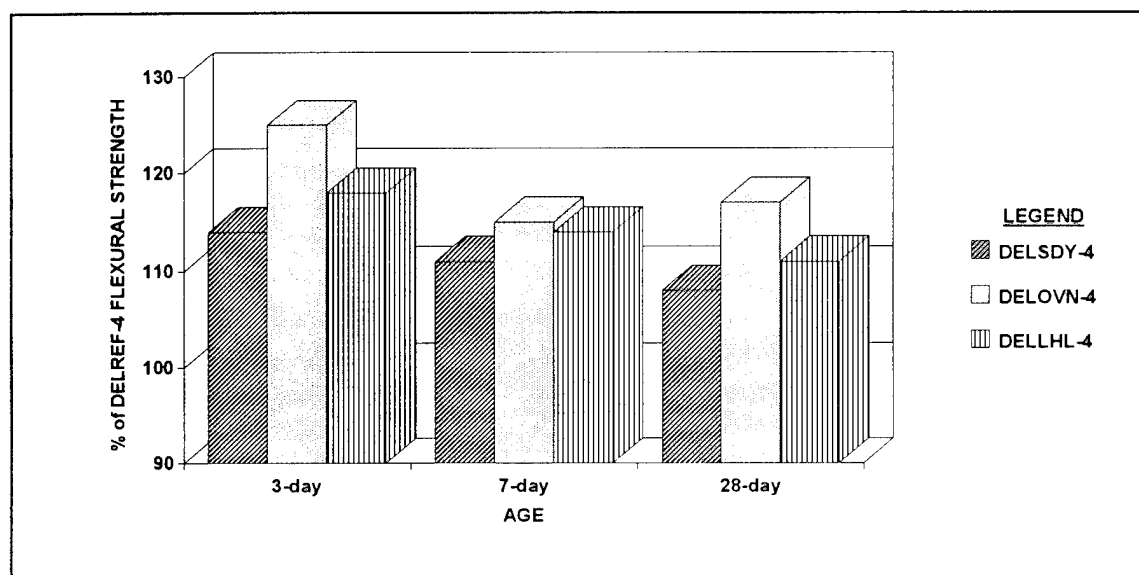
Figure 8.   Relative flexural-strength comparison between stabilized mixtures and reference mixture DELREF-4

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averages of the individual durability factors are provided in Table 12. The average durability factors for the reference mixtures ranged from 86 to 90. The relative durability factors shown in Table 12 provide a comparison of the durability factors of the stabilized mixtures to those of the reference mixtures. The relative durability factor for each mixture was calculated by dividing the stabilized mixture durability factor by the respective reference mixture durability factor and multiplying the quotient by 100. ASTM C 494 (ASTM 1991i) requires that concrete containing chemical admixtures have relative durability factors when compared with reference mixtures without the admixture under test of at least 80. Although the stabilized mixtures were prepared much differently from those that would be tested in accordance with ASTM C 494 (ASTM 1991i), a relative durability factor of 80 seems a useful benchmark to use for evaluating the resistance to freezing and thawing of the stabilized mixtures. All of the stabilized mixtures except DELOVN-4 have average relative durability factors equal to or greater than 80. The fact that all of the stabilized mixtures are judged as relatively resistant to cycles of freezing and thawing is not surprising since the concrete met the three factors required for frost resistance. That is, it was made with nonfrost-susceptible aggregates, it contained a proper air-void system, and it was cured to an appropriate degree of maturity so as to reduce the fractional volume of freezable water on saturation to limits that can be accommodated by elastic volume change and by the air-void system. Mixtures DELOVN-4 and DELOVN-2 had relative durability factors of 78 and 80, respectively. The average fresh air contents of the batches representing these mixtures were 5.5 and 6.5 percent, respectively, and hardened samples representing the mixtures had air-void spacing factors of 0.0055 and 0.0038 in., respectively. Spacing factors less than 0.008 in. are typically associated with concrete that has good resistance to freezing and thawing.

Length change

One length-change prism was molded from each batch after all admixtures and new concrete, as applicable, were batched and mixed. The prisms were cured in accordance with procedures described in ASTM C 494 (ASTM 1991i) except that instead of moist curing them for 14 days followed by air storage for 14 days, they were moist cured for 28 days and stored in air for 28 days. The individual length-change measurements are given in Table B4, Appendix B, and the averages of the individual length-change measurements are shown in Table 13. The average length change of the reference mixtures ranges from -0.018 to -0.032 in. A negative value indicates that shrinkage occurred during the drying period. ASTM C 494 (ASTM 1991i) states that if the length change of the reference concrete after 14 days drying is less than 0.030 percent, the length change on drying of the concrete containing the admixture shall not be more than 0.010 percent greater than that of reference concrete. Although the stabilized mixtures do not represent concrete prepared with chemical admixtures as described in ASTM C 494 (ASTM 1991i), the

Table 12
Summary of Rapid Freezing-and-Thawing Test Results
(Laboratory-Temperature Concrete)

Mixture	Average Durability Factor	Durability Factor Relative to Respective DELREF Mixture
DELREF-1	86	100
DELSDY-1	85	99
DELOVN-1	84	98
DELLHL-1	92	107
DELREF-2	86	100
DELSDY-2	86	100
DELOVN-2	69	80
DELLHL-2	92	107
DELREF-3	90	100
DELSDY-3	90	100
DELOVN-3	92	102
DELLHL-3	94	104
DELREF-4	89	100
DELSDY-4	88	99
DELOVN-4	69	78
DELLHL-4	90	101

criteria cited are useful for comparing shrinkage of the stabilized mixtures to that of the respective reference mixtures. The average length-change measurements shown in Table 13 indicate that the variations in length change of all of the same-day- and long-haul-stabilized mixtures were less than 0.010 percent of those of the respective reference mixtures. Half of the same-day- and long-haul-stabilized mixtures experienced less shrinkage than the reference mixtures. However, the overnight-stabilized mixtures generally experienced more shrinkage at 28-days age under the curing and storage conditions described than the other stabilized mixtures, and DELOVN-2 and DELOVN-4 had average length-change values greater than 0.010 percent of the respective reference mixtures. The higher shrinkage values of the overnight-stabilized mixtures cannot be attributed to additional mixing water since the total water contents of these mixtures were the same as those of the respective reference mixtures. The higher dosages of DELVO Stabilizer used in the overnight mixtures (2 to 7 times that used in the other stabilized mixtures) combined with the use of the Pozzutec 20 accelerating admixture to reactivate the stabilized concrete may be responsible for the increased shrinkage in these

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Table 13
Summary of Length Change Test Results
(Laboratory-Temperature Concrete)

Mixture	Average Length Change, percent	Variation in Length Change from Respective DELREF Mixture, percent
DELREF-1	-0.018[1]	0.000
DELSDY-1	-0.026	0.008 >[2]
DELOVN-1	-0.039	0.021 >
DELLHL-1	-0.024	0.006 >
DELREF-2	-0.032	0.000
DELSDY-2	-0.028	0.004 <
DELOVN-2	-0.042	0.010 >
DELLHL-2	-0.030	0.002 <
DELREF-3	-0.020	0.000
DELSDY-3	-0.015	0.005 <
DELOVN-3	-0.029	0.009 >
DELLHL-3	-0.026	0.006 >
DELREF-4	-0.026	0.000
DELSDY-4	-0.034	0.008 >
DELOVN-4	-0.042	0.016 >
DELLHL-4	-0.026	0.000

[1] A negative sign indicates shrinkage occurred.
[2] > indicates length change was greater than that of the respective reference mixture, whereas < indicates that the length change was less than that of the reference mixture.

mixtures. In general, accelerated mixtures are expected to exhibit greater shrinkage than mixtures that are not treated with accelerating admixtures.

Resistance to chloride-ion penetration

One 4- by 8-in. cylindrical specimen was molded from each batch after all admixtures and new concrete, as applicable, were batched and mixed. The individual test results, expressed as coulombs passed, are given in Table B5, Appendix B. These results appear somewhat variable for some of the mixtures, although the precision statements given in ASTM C 1202 (ASTM 1992k) indicate indirectly that this test has a relatively high degree of variability associated with it. Consequently, caution is warranted in using the data to evaluate the performance of the concretes. Averages of the individual

results are provided in Table 14. Figure 9 graphically presents the data from Table 14. Based upon qualitative estimates of chloride-ion penetrability given in ASTM C 1202 (ASTM 1992k), both the reference and stabilized mixtures have moderate-to-high chloride-ion penetrability and were comparable.

Parameters of air-void system

Twelve samples were examined to determine the air-void system parameters of the reference and stabilized mixtures. One sample was examined for each mixture condition. The results of these examinations are given in Table 15. Since spacing factors less than 0.008 in. are associated with concrete having good frost resistance, each of the mixtures should be frost resistant. This observation was confirmed based upon the results of the freezing-and-thawing tests. It is interesting to note that some of the mixtures have relatively low entrained-air contents and yet still have small spacing factors. This may be due in part to the use of the Micro Air AEA in the concrete. Neeley, McDonald, and Lloyd (1992) reported that the use of this AEA resulted in concrete that had smaller spacing factors and higher specific surfaces at lower air contents than five other AEA's tested.

Table 14
Summary of Chloride-Ion Penetration Test Results
(Laboratory-Temperature Concrete)

Mixture	Average Charge Passed, coulombs
DELREF-1	3,150
DELSDY-1	3,247
DELOVN-1	4,305
DELLHL-1	2,980
DELREF-2	4,893
DELSDY-2	4,357
DELOVN-2	7,003
DELLHL-2	4,353
DELREF-3	4,197
DELSDY-3	3,290
DELOVN-3	3,073
DELLHL-3	3,123
DELREF-4	5,610
DELSDY-4	3,943
DELOVN-4	4,970
DELLHL-4	4,243
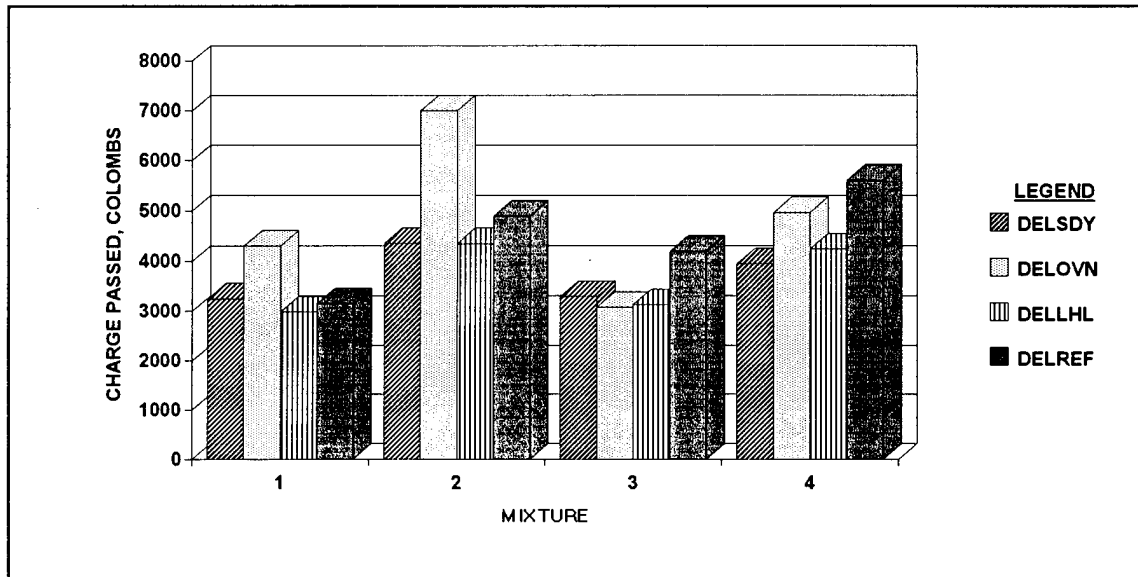
Figure 9.   Chloride-ion penetration results of laboratory-temperature concrete

Table 15
Air-Void System Parameters (Laboratory-Temperature Concrete)

Mixture	Paste Volume, percent	Entrapped Air Content, percent	Entrained Air Content, percent	Total Air Content, percent	Spacing Factor, in.
DELREF-1	23.5	3.8	2.1	5.9	0.0067
DELSDY-1	23.9	2.5	2.0	4.5	0.0060
DELOVN-1	21.5	1.4	3.4	4.8	0.0050
DELLHL-1	19.8	1.6	3.1	4.7	0.0048
DELREF-2	25.4	1.7	1.3	3.0	0.0045
DELSDY-2	23.1	2.6	2.3	4.9	0.0066
DELOVN-2	21.2	1.2	5.2	6.4	0.0038
DELLHL-2	22.5	1.8	4.1	5.9	0.0048
DELREF-3	27.5	1.7	3.1	4.8	0.0053
DELSDY-3	27.0	2.1	2.7	4.8	0.0058
DELOVN-3	30.2	1.5	4.5	6.0	0.0048
DELLHL-3	27.9	2.2	2.0	4.2	0.0065
DELREF-4	29.8	1.7	2.8	4.5	0.0054
DELSDY-4	26.9	1.1	1.7	2.8	0.0060
DELOVN-4	28.4	1.0	3.5	4.5	0.0055
DELLHL-4	29.8	1.0	1.4	2.4	0.0057

Hardened Concrete Tests—Elevated Temperature

Compressive strength and modulus of elasticity

Only the low-cement-content reference and same-day-stabilized mixtures were batched and mixed at a nominal temperature of 95° F. Five cylinders were molded from each batch after all admixtures and new concrete, as applicable, were batched and mixed. The individual compressive-strength and modulus-of-elasticity test results for these mixtures are given in Table B6, Appendix B. The averages of the individual results are shown in Table 16. Figure 10 provides a relative comparison between the compressive strengths of the same-day-stabilized mixtures and those of the respective reference mixtures. The compressive strengths of all the same-day-stabilized mixtures exceed approximately 90 percent of those of the reference mixtures at all ages. The strengths of the DELSDYH-1 mixture are greater than those of reference mixture DELREFH-1 at all ages, while the strengths of mixture DELSDYH-2 are approximately 90 percent of those of reference mixture DELREFH-2 at all ages except 3-days age. Although the fresh concrete properties of the respective reference and same-day-stabilized mixtures are comparable, differences in the cement properties may have a more pronounced effect on compressive strengths of the stabilized mixtures at elevated concrete temperatures.

The modulus-of-elasticity values for the reference and respective same-day-stabilized mixtures are within 5 percent of one another. Because the w/c and temperature of these mixtures were higher than those of the laboratory-temperature mixtures, one might expect the compressive strengths and modulus-of-elasticity values of the elevated-temperature mixtures to be lower. However, in fact those test results were quite comparable.

Table 16
Summary of Compressive Strength and Modulus-of-Elasticity Test Results (Elevated-Temperature Concrete)

Mixture	Average Compressive Strength, psi					28-day Modulus of Elasticity, 10^6 psi
	1-day	3-day	7-day	28-day	6-month	
DELREFH-1	1,717	2,547	3,057	4,123	5,177	5.54
DELSDYH-1	1,740	2,707	3,167	4,270	5,583	5.79
DELREFH-2	1,830	2,993	3,807	4,623	5,207	5.24
DELSDYH-2	1,670	3,203	3,437	4,137	4,813	5.10
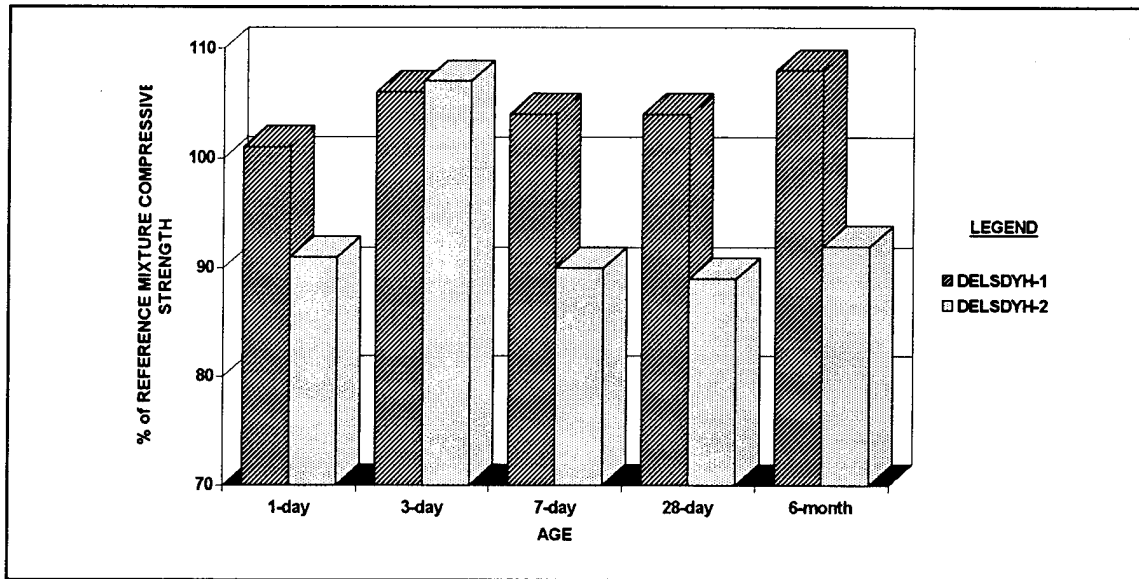
Figure 10. Relative compressive-strength comparison between reference mixtures and same-day-stabilized mixtures (elevated concrete temperature)

Flexural strength

Three beams were molded from each batch of the low-cement content reference and same-day-stabilized mixtures after all admixtures and new concrete, as applicable, were batched and mixed. The individual flexural-strength test results are given in Table B7, Appendix B. The averages of the individual test results are summarized in Table 17. Figure 11 shows that for all ages, the same-day flexural strengths are 98 percent or greater than those of the respective reference mixtures. The average relative flexural strengths of mixture DELSDYH-2 are slightly less than those of DELSDYH-1 at all ages, which is consistent with the trend noted for the elevated-temperature concrete compressive-strength results. The flexural-strength test results are also comparable to those of the laboratory-temperature concrete mixtures, which is also consistent with compressive-strength test results.

Table 17
Summary of Flexural-Strength Test Results
(Elevated-Temperature Concrete)

Mixture	3-day, psi	7-day, psi	28-day, psi
DELREFH-1	428	582	690
DELSDYH-1	530	618	732
DELREFH-2	545	675	742
DELSDYH-2	600	662	742
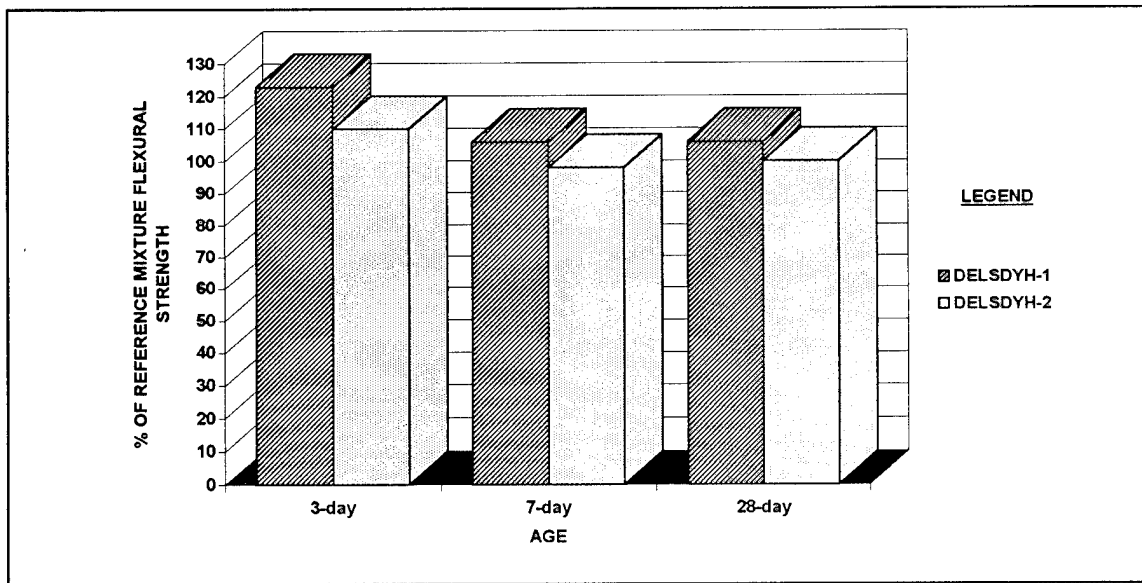
Figure 11. Relative flexural-strength comparison between reference mixtures and same-day-stabilized mixtures (elevated-temperature concrete)

Resistance to rapid freezing and thawing

One prism was molded from each batch of the low-cement-content reference and same-day-stabilized mixtures after all admixtures and new concrete, as applicable, were batched and mixed. The individual durability factors are given in Table B8, Appendix B, and average durability factors are summarized in Table 18. The relative durability factors of the same-day-stabilized mixtures are greater than 100, indicating no loss in frost resistance in the stabilized mixtures.

Table 18
Summary of Rapid Freezing-and-Thawing Test Results (Elevated-Temperature Concrete)

Mixture	Average Durability Factor	Relative Durability Factor to DELREFH Mixtures
DELREFH-1	83	100
DELSDYH-1	85	106
DELREFH-2	88	100
DELSDYH-2	89	105

Length change

One length-change prism was molded from each batch of low-cement content reference and same-day-stabilized mixture after all admixtures and new concrete, as applicable, were batched and mixed. Curing and storage were the same as noted for the laboratory-temperature concrete length-change specimens. Individual length-change test results are given in Table B9, Appendix B, and Table 19 summarizes averages of the individual test results. Although the ASTM C 494 (ASTM 1991i) maximum allowable limit of 0.010 percent length change in excess of that for the reference concrete is not strictly applicable for these concretes, it does provide a convenient basis for comparison. Both same-day mixtures experienced shrinkage approaching 0.010 percent greater than the respective reference mixtures, indicating that drying shrinkage may be a concern at elevated concrete temperatures. For this test, the shrinkage was within the limits of ASTM C 494 (1991i) and ASTM C 157 (1991c).

Table 19
Summary of Length-Change Test Results (Elevated-Temperature Concrete)

Mixture	Average Length Change, percent	Variation in Length Change from Respective DELREFH Mixture, percent
DELREFH-1	-0.014[1]	0.000
DELSDYH-1	-0.023	0.009 >[2]
DELREFH-2	-0.025	0.000
DELSDYH-2	-0.035	0.010 >

[1] A negative sign indicates shrinkage occurred.
[2] > indicates length change was greater than that of the respective reference mixture.

Resistance to Chloride-ion penetration

One 4- by 8-in. cylinder was molded from each batch of the low-cement content reference and same-day-stabilized mixtures after all admixtures and new concrete, as applicable, were batched and mixed. The individual test results are shown in Table B10, Appendix B, and the averages of the individual test results are given in Table 20. The average coulombs-passed values indicate that the reference and same-day-stabilized mixtures are comparable, and each has moderate-to-high chloride-ion penetrability.

Table 20 Summary of Chloride-Ion Penetration Test Results (Elevated-Temperature Concrete)	
Mixture	Average Charge Passed, coulombs
DELREFH-1	3,960
DELSDYH-1	3,310
DELREFH-2	4,663
DELSDYH-2	4,223

5 Use of DELVO in Lean Mass Concrete

Cracking Considerations in Mass Concrete

One characteristic that distinguishes mass concrete from other types of concrete is thermal behavior. The American Concrete Institute (ACI) defines mass concrete as "any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking" (ACI 1994). Cracking in mass concrete is caused by restraint of volume change. These volume changes may be due to heat generation and subsequent cooling, shrinkage, creep or stress relaxation, or other mechanisms. Restraint limits the change in dimensions and causes corresponding tensile, compressive, or flexural stresses in concrete. The restraint that causes tensile stresses, particularly in the first few days after placement of the concrete when the tensile strain capacity of the concrete can be quite low, is of particular concern in mass-concrete structures. Restraint of volume change may be from external or internal sources. External restraint is caused by bond or frictional forces between the concrete and the foundation or underlying concrete lifts. The degree of external restraint depends on the geometry of the section and upon the strength and stiffness of the concrete and restraining material. Internal restraint is caused by temperature gradients within the concrete. The warmer concrete in the interior of the lift provides restraint as the concrete in the periphery of the lift cools due to heat transfer to its surroundings. The degree of internal restraint depends upon the quantity of heat generated, the thermal properties of the concrete, and the thermal boundary conditions.

Measures should be taken where cracking jeopardizes structural integrity and monolithic action, or may cause excessive seepage and shorten structural service life, or may be aesthetically objectionable. Cracking in mass concrete may be limited by controlling several material and construction parameters. Material parameters that may be controlled include heat generation of the concrete; mechanical properties of the concrete including strength, modulus of elasticity, and creep or stress relaxation; shrinkage of the concrete; and thermal properties including coefficient of thermal expansion, specific heat, and thermal conductivity. Construction parameters that may be controlled

include lift height; time between placement of lifts; placement temperature; ambient temperature; use of insulation; use of cooling coils; and monolith geometry including section thickness, monolith length, and location and size of inclusions such as galleries and culverts.

Objectives of DELVO Mass-Concrete Investigation

The primary objective of this laboratory investigation was to determine if the use of DELVO Stabilizer in lean mass-concrete typical of that used by the USACE in construction of civil works structures would favorably affect selected thermal and mechanical properties without detrimentally affecting time of setting. Data generated in an earlier mass-concrete materials properties investigation conducted by WES for the McAlpine Locks Replacement, Louisville District, was used to evaluate the effects of DELVO Stabilizer on mass-concrete properties.

Scope of DELVO Mass-Concrete Investigation

In order to compare selected properties of lean mass concrete containing DELVO Stabilizer with a reference mixture containing no DELVO, the same materials used in the McAlpine materials study were used to proportion and produce a DELVO mass-concrete mixture. Preliminary laboratory work was conducted by WES with the assistance of Master Builders staff to determine the appropriate DELVO Stabilizer dosage. Concrete containing the DELVO Stabilizer was batched and mixed, sampled, and tested for temperature, slump, unit weight, air content, time of setting, adiabatic temperature rise, compressive strength, modulus of elasticity, creep, and ultimate strain capacity. Test results were then compared with those generated in the McAlpine materials study on the same basic mixture without DELVO.

Mass-Concrete Materials and Mixture

The Louisville District is planning to construct a navigation lock on the Ohio River at Louisville, KY, to replace the two existing McAlpine Locks that are inadequate to meet current and future navigation requirements. As part of a nonlinear incremental structural analysis (NISA) study conducted on the planned replacement lock, WES conducted a materials study for the Louisville District to proportion concrete mixtures similar to those likely to be used to construct the replacement lock and to determine thermal and mechanical properties of the concrete for input into the NISA finite element analyses. The materials used in the McAlpine materials study were selected by the Louisville District as typical of what might be chosen by a contractor for construction of the structure. The materials selection was based upon a knowledge of potential sources of cementitious materials and aggregates in the

vicinity of the proposed project site. The same materials used in the McAlpine study were also used in the DELVO mass concrete investigation.

The portland cement selected for use conformed to ASTM C 150 (ASTM 1992c) Type II, low-alkali requirements. The optional 7-day requirement for heat of hydration was not invoked. Chemical and physical properties of the cement are given in Table 21. A Class F fly ash conforming to ASTM C 618 (ASTM 1992i) was also used in the concrete mixtures. Table 22 presents the chemical and physical properties of the fly ash. Three size groups of crushed limestone coarse aggregates were used in the study. The nominal maximum coarse aggregate size was 75 mm (3 in.). The fine aggregate was a natural siliceous sand. The gradings, absorptions, and bulk specific gravities for the coarse and fine aggregates are given in Table 23.

Specific concrete property requirements for mixtures used in the McAlpine materials study were set by the Louisville District. Two mass-concrete mixtures were proportioned and tested in the McAlpine study. One of these was for use in the interior of the structure and one for use in the exterior portion. The interior mixture was selected by WES for use in the DELVO mass-concrete study since interior mass concrete normally makes up the largest volume of mass concrete used in construction of any Corps of Engineers navigation lock. The required compressive strength of the McAlpine interior mixture was 2,000 psi at 90-days age. In addition, a strength requirement of 500 psi at the time of erection of the forms for the next lift (typically approximately 2 days) was imposed for formwork anchorage considerations. At strengths less than 500 psi, special formwork anchorages may be required, thus potentially increasing construction costs. The required air content on that portion of the mixture finer than the 37.5-mm (1-1/2) sieve was 4 to 7 percent, and the required slump was 1 to 3 in.

The DELVO Stabilizer dosage used in the McAlpine interior mixture was based upon the assumption that the maximum dosage possible should be used to minimize adiabatic temperature rise in the concrete. However, the time of setting and strength gain could not be retarded to the extent that the 2-day strength of 500 psi could not be attained. A series of mixtures were proportioned in order to empirically determine the appropriate DELVO Stabilizer dosage. Tests conducted on these mixtures included slump, air content, unit weight, time of setting, compressive strength, and Q-Drum tests. All tests except the Q-Drum, formerly called the Haybox, are standard ASTM tests. The Q-Drum is a device that measures the heat signal from a 6- by 12-in. cylinder of fresh concrete in a calibrated calorimeter. It couples the heat signal with heat capacity information entered for the individual components of the concrete and calibrates an adiabatic temperature rise for the concrete. The limitation of the device is the duration of the test. Since there is no heat supplied to the system, the adiabatic temperature rise can be determined only through the time it takes for the specimen to lose hydration heat and return to ambient temperature, which is typically approximately

Table 21
Report of Tests on Hydraulic Cement

Chemical Analysis		
Properties	**Result**	**ASTM C 150 Spec. Limits, Type II**
SiO_2, percent	21.5	20.0 min
Al_2O_3, percent	4.0	6.0 max
Fe_2O_3, percent	3.5	6.0 max
CaO, percent	63.5	--
MgO, percent	2.6	6.0 max
SO_3, percent	2.4	3.0 max
Loss on Ignition, percent	1.3	3.0 max
Insoluble residue, percent	0.24	0.75 max
Na_2O, percent	0.15	--
K_2O, percent	0.70	--
Alkalies-total as Na_2O, percent	0.62[2]	0.60 max
TiO_2, percent	0.27	--
P_2O_5, percent	0.08	--
C_3O, percent	6	--
C_3S, percent	54	--
C_2S percent	21	--
C_4AF, percent	11	1.5 max
Physical Tests		
Heat of hydration, 7-day, cal/g	76[2]	70[1]
Surface area, m^2/kg (air permeability)	366	280 min
Autoclave expansion, percent	0.00	0.80 max
Initial set, min (Gillmore)	235	60 min
Final set, min (Gillmore)	300	600 max
Air content, percent	10	12 max
Compressive strength, 3-day, psi	3,300	1,500, 1,000[1] min
Compressive strength, 7-day, psi	4,030	2,500, 1,700[1] min
False set (final penetration), percent	94	50 min

Note: Identification of Sample

Company: Kosmos Cement, Kosmosdale, KY   Sampling Date: 30 July 1992
Test Report No.: ORL-142-92

[1] Applies only when optional limit on heat of hydration is invoked.
[2] Heat of hydration limit and low alkali were not project specification requirements.

Table 22
Report of Tests on Pozzolan

Chemical Analysis		
Properties	**Result**	**ASTM C 618 Spec. Limits, Class F**
SiO_2, percent	53.7	--
Al_2O_3, percent	23.6	--
Fe_2O_3, percent	9.2	--
Sum, percent	86.5	70.0 min
CaO Factor, percent	--	--
R Factor	--	--
MgO, percent	0.7	--
SO_3, percent	0.6	5.0, 4.0 max
Moisture content, percent	0.1	3.0 max
Loss on ignition, percent	2.9	6.0, 2.5 max
Available alkalies, 28-day, percent	0.9	1.5 max
Physical Tests		
Fineness (45 μm), percent retained	23	34 max
Fineness variation, percent	--	5 max
Water requirement, percent	100	105 max
Density, Mg/m^3	2.26	--
Density variation, percent	--	5 max
Autoclave expansion, percent	-0.03	0.80 min
Pozzolanic activity w/lime, psi	1,000	800 min
Strength activity index w/cement, 7-day, percent	77	75 min
Strength activity index w/cement, 28-day percent	--	75 min

Identification of Sample

Company: Burgin Fly Ash   Location: Burgin, Kentucky
Sampling Date: 30 July 1992   Test Report No.: ORL-141F-92

Cement used: Kosmos, Kosmosdale, KY 142-92

Lime used: Chemstone

Table 23
Aggregate Properties

Sieve Size	37.5 - 75 mm (1-1/2 - 3 in.)	19.0 - 37.5 mm (3/4 - 1-1/2 in.)	4.75 - 19.0 mm (No. 4 - 3/4 in.)	4.75 - 150 μm (No. 4 - No. 100)
75 mm (3 in.)	97			
50 mm (2 in.)	38	100		
37.5 mm (1-1/2 in.)	12	99		
25.0 mm (1 in.)	9	38	100	
19.0 mm (34/ in.)	8	9	99	
12.5 mm (1/2 in.)		4	53	
9.5 mm (3/8 in.)		3	18	100
4.75 mm (No. 4)		3	3	95
2.36 mm (No. 8)			3	85
1.18 mm (No. 16)				75
600 μm (No. 30)				57
300 μm (No. 50)				14
150 μm (No. 100)				2
Bulk Specific Gravity (S.S.D.)	2.64	2.65	2.67	2.62
Absorption, %	2.90	2.24	2.67	1.40

7 days. The Q-Drum tests were used to assist in screening the trial mixtures. Based upon the results of the trial batches, the decision was made to use a DELVO Stabilizer dosage of 23 oz/100-lb cement. Upon recommendation of Master Builders, the fly ash was excluded from consideration for purposes of dosage calculation. The use of DELVO Stabilizer permitted a water reduction in the original McAlpine interior mixture of approximately 5 percent. The cement content of the mixture was not reduced so that proper workability could be maintained; therefore, the water reduction resulted in a reduction of the w/c of 0.03. The proportions of the McAlpine interior mixture and the DELVO mass-concrete mixture selected for the test are shown in Table 24.

Table 24
Mass-Concrete Mixture Proportions

Mixture	Portland Cement	Fly Ash	37.5 - 75.0 mm	19.0 - 37.5 mm	4.75 - 19.0 mm	Fine Aggregate	Water	w/c	DELVO Stabilizer, oz/100-lb cement
	Saturated Surface-Dry Weights, lb/yd³								
McAlpine	176	126	1,359	570	550	1,001	176	0.50	none
DELVO	176	126	1368	574	553	1082	165	0.47	23

Testing of DELVO Mass-Concrete Mixture

Along with standard fresh concrete tests, a series of selected mechanical and thermal properties tests was conducted on a single batch of the DELVO mass-concrete mixture so that a comparison could be made with those properties of the McAlpine interior mixture. Fresh concrete tests included temperature, slump, air content, unit weight, and time of setting. Test methods followed in conducting these tests are noted in Chapter 3 of this report. Mechanical properties tests conducted included compressive strength, modulus of elasticity, creep, sealed length change, and ultimate strain capacity. Compressive-strength tests were conducted in accordance with ASTM C 39 (ASTM 1992a) at 3-, 7-, 14-, and 28-days age. Due to the limited size of the concrete batch (14 ft^3) and the large total number of test specimens required, the decision was made not to conduct compressive-strength tests at 90-days age.

Modulus-of-elasticity tests were conducted at 3-, 7-, 14-, and 28-days age using strain-gaged compressive-strength specimens in accordance with ASTM C 469 (ASTM 1992g). At 3-days age or less, stress-strain data for the mixtures exhibited limited elastic compression behavior; however, values for elastic modulus at early ages are necessary for calibrating the time-dependent material model used in the McAlpine NISA.

Creep is time-dependent deformation due to sustained load. Creep is the deformation in excess of shrinkage strains and elastic strains. Upon initial application of load at time, t_0, the material response is primarily elastic, but includes an inelastic component. The nominal elastic strain is governed by the elastic modulus at time, $t - t_0$. Because elastic modulus increases with time (rapid at early ages) the elastic component of strain decreases with time. It is common practice to ignore this change in elastic modulus with time and use the nominal elastic strain except for special considerations. This phenomenon is an important consideration in the calibration of the time-dependent model used in the McAlpine NISA. Deformation due to causes other than load or temperature change (termed shrinkage) when shortening occurs is measured by monitoring the deformation of unloaded specimens prepared identically to the creep specimens. Thus, creep strains are calculated from the total measured strains as follows:

$$\epsilon_{creep} = \epsilon_{total} - \epsilon_{elastic} - \epsilon_{shrinkage}$$

where

ϵ = strain

Using this concept, two creep tests were conducted according to ASTM C 512 (ASTM 1992h) modified to include continuous data acquisition under computer control at ages of 3 and 14 days. The cylindrical specimens were 6 by 16 in. long and were cast in steel molds with the longitudinal axis horizontal. These molds accommodated 8-in.-long Carlson strain gages placed

at the center of the specimens oriented along the longitudinal axis of the cylinder. Steel bearing plates were attached to the ends of the specimens by embedded mechanical anchors. These plates provided a smooth, plane surface for applying the compressive force. After the specimens were cast, the exposed surfaces were covered with moist burlap and plastic film to prevent drying. The specimens were demolded; and a bituminous moisture barrier, a rubber-like membrane with bituminous adhesive, was applied to the surface of the creep specimens at approximately 20 hr to prevent moisture from entering or leaving the specimen. The apparatus used to perform the creep tests was a hydraulic loading frame designed to maintain a constant stress by means of a gas pressure regulator in series with a gas/oil accumulator and hydraulic ram. Creep specimens were loaded to 30 percent of the unconfined compressive strength at the age of loading as determined from the compressive-strength tests on companion 6- by 12-in. cylinders.

Two specimens having the same dimensions as the creep specimens were cast and demolded and stored in the same manner as the creep specimens. These specimens were used to measure strain in a sealed condition not associated with applied loads. In order to simulate the early-age material response properly, this volume-change phenomenon must be included in the material model used in the NISA study.

Ultimate strain capacity test results are used to establish experimental failure criterion for the material and cracking model used in a NISA study. An ultimate strain capacity test series consisting of three beam tests on specimens from the McAlpine interior mixture was performed in accordance with CRD-C 71 (USACE 1949a). These tests were conducted by loading the beams in third-point loading according to applicable provisions of ASTM C 78 (ASTM 1992b). The test series consisted of one test series loaded to failure using a rapid-loading rate of 40-psi/min fiber stress at 7-days age. A second beam was loaded at 7-days age in a slow-loading cycle of 25 psi/week until failure occurred. Upon failure of the second beam, a third beam was tested to failure using the rapid-loading rate. For comparison purposes, only one beam was tested from the DELVO mass-concrete mixture at 7-days age using the rapid-loading rate. The beam was 12 in. wide by 12 in. high by 66 in. long and was cast in a steel mold. Carlson strain gages, 8 in. long, were attached to the mold and embedded 1-1/2 in. from and parallel to the top (compression) and bottom (tensile) surfaces. After the beam was cast, it was covered with moist burlap and plastic film to prevent drying of the exposed surface. At 6-days age, the beam was demolded and wrapped in the same bituminous moisture barrier used to seal the creep test specimens. Rapid loading was accomplished using a 50,000-lbf electro-hydraulic loading system. Loads and strains were recorded using a digital data acquisition system. The loading rate was set to 1,152-lbf/min to cause a 40 psi/min increase in extreme fiber stress.

Characterization of the thermal properties of the McAlpine interior mixture was based upon adiabatic temperature rise, thermal diffusivity, specific heat, thermal conductivity, and coefficient of linear expansion test results. For

comparison purposes, the DELVO mass-concrete mixture was tested only for adiabatic temperature rise. The temperature rise of concrete in an adiabatic condition is primarily due to hydration of the cement and pozzolanic reaction of the pozzolan that make up the cementitious materials. The magnitude and shape of the adiabatic temperature rise versus time curve are important measures of the heat-generating potential of a concrete mixture. These data are used as the forcing function for the calculation of temperature distribution throughout a structure. One adiabatic temperature rise test was conducted on the DELVO mass-concrete mixture in accordance with CRD-C 38 (USACE 1949b). The test was conducted in a computer-controlled adiabatic calorimeter which maintained conditions such that no heat was lost during the test. The test specimen was a 30-in.-diam by 29-in.-high cylinder. Monitoring of adiabatic temperature rise continued for 27 days.

DELVO Mass-Concrete Test Results

The results of the fresh tests on the DELVO mass-concrete mixture and the McAlpine interior mixture are given in Table 25. All but the time-of-setting results are comparable. The use of the high dosage of DELVO Stabilizer retarded both the initial and final times of setting significantly. Although this caused some concern due to the potential for delays in preparing horizontal lift joints, it was believed that as long the 500-psi strength at 2- to 3-days age was achieved, the severe retardation would not be objectionable.

Table 25
Fresh Mass-Concrete Test Results

Mixture	Temperature, °F	Slump,[1] in.	Unit[1] Wt, lb/ft³	Air[1] Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELVO	65	2-1/2	144.0	4.6	18:05	22:23
McAlpine	67	3	145.5	5.9	7:33	11:14

[1] Conducted on that portion of sample finer than 37.7-mm sieve.

The compressive-strength and modulus-of-elasticity test results for both mass-concrete mixtures are given in Table 26. Figures 12 and 13, respectively, present the compressive-strength and modulus-of-elasticity results plotted versus age. Both the compressive-strength and modulus-of-elasticity curves of the DELVO mass-concrete mixture parallel those of the McAlpine interior mixture, but are somewhat higher. This is likely due to the lower w/c of the DELVO mixture resulting from the water-reducing effect of the DELVO. The higher compressive strengths and moduli of elasticity indicate the DELVO mixture is slightly stiffer than the McAlpine mixture at all ages which might result in higher thermal stresses.

Table 26 Summary of Compressive-Strength and Modulus-of-Elasticity Results				
Mixture	**3-day**	**7-day**	**14-day**	**28-day**
Compressive Strength, psi				
DELVO	895	1320	1695	2350
McAlpine	790	1100	1450	2020
Modulus of Elasticity, 10^6 psi				
DELVO	1.86	2.95	3.13	3.90
McAlpine	1.78	2.30	2.64	3.33
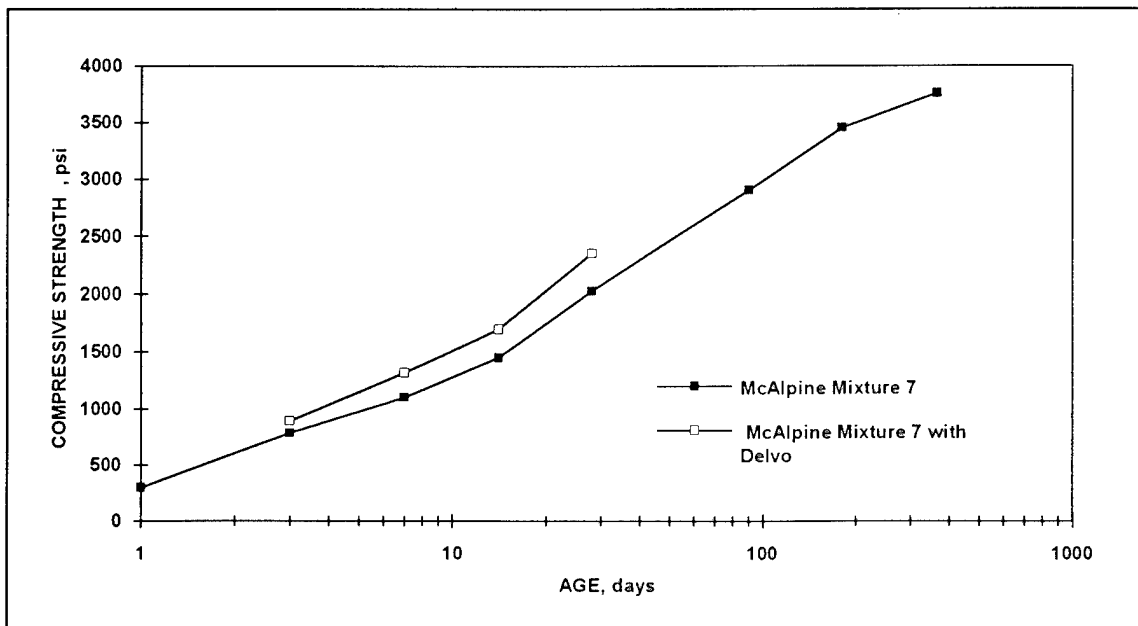
Figure 12. Compressive-strength results of DELVO and McAlpine mass-concrete mixtures
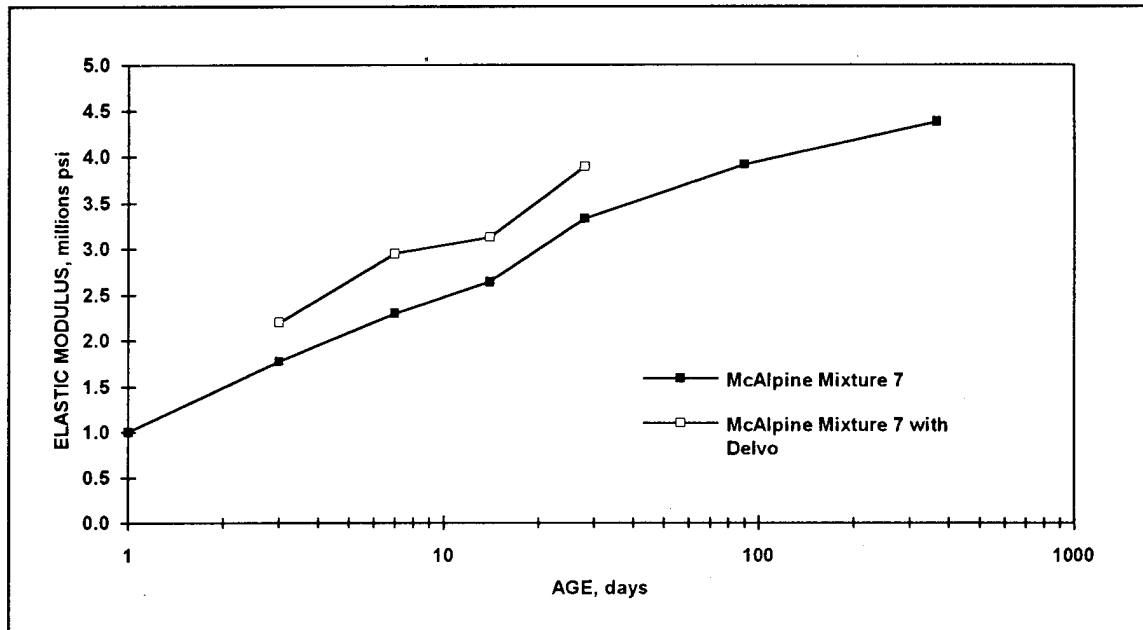
Figure 13. Modulus-of-elasticity results of DELVO and McAlpine mass-concrete mixtures

The data from creep tests were reduced as specified in ASTM C 512 (ASTM 1992h). The procedure requires that the strains which occur during the initial loading and strains recorded by the shrinkage compensation cylinders be subtracted from the measured strains. These corrected strains were then divided by the average sustained stress to obtain specific creep. Specific creep data are presented in Figure 14. Noteworthy observations include the fact that the specific creep for each mixture decreases with increasing age of loading. This decrease in creep response is related to increase in modulus of elasticity and strength due to continuing cement hydration. The specific creep of the DELVO mixtures is lower than that of the McAlpine mixture at loading ages of both 3 and 14 days. This is not surprising since both the strength and modulus of elasticity at these ages are higher for the DELVO mixture than for the McAlpine mixture. One potential effect of lower specific creep in the DELVO mixture could be higher thermally induced stresses in the mass concrete.

The 7-day ultimate strain capacity test results are given in Table 27. The extreme fiber strain was determined at 90 percent of the modulus of rupture, and this strain is reported as ultimate strain capacity. The DELVO mixture had approximately 11-percent higher ultimate tensile strain capacity than for the McAlpine mixture, which would enable it to sustain slightly higher tensile stresses in a rapid-loading condition before failure than the McAlpine mass concrete mixture. The tensile stress-strain curves for the two mixtures shown in Figure 15 indicate that the rate of strain development for both mixtures is essentially identical.
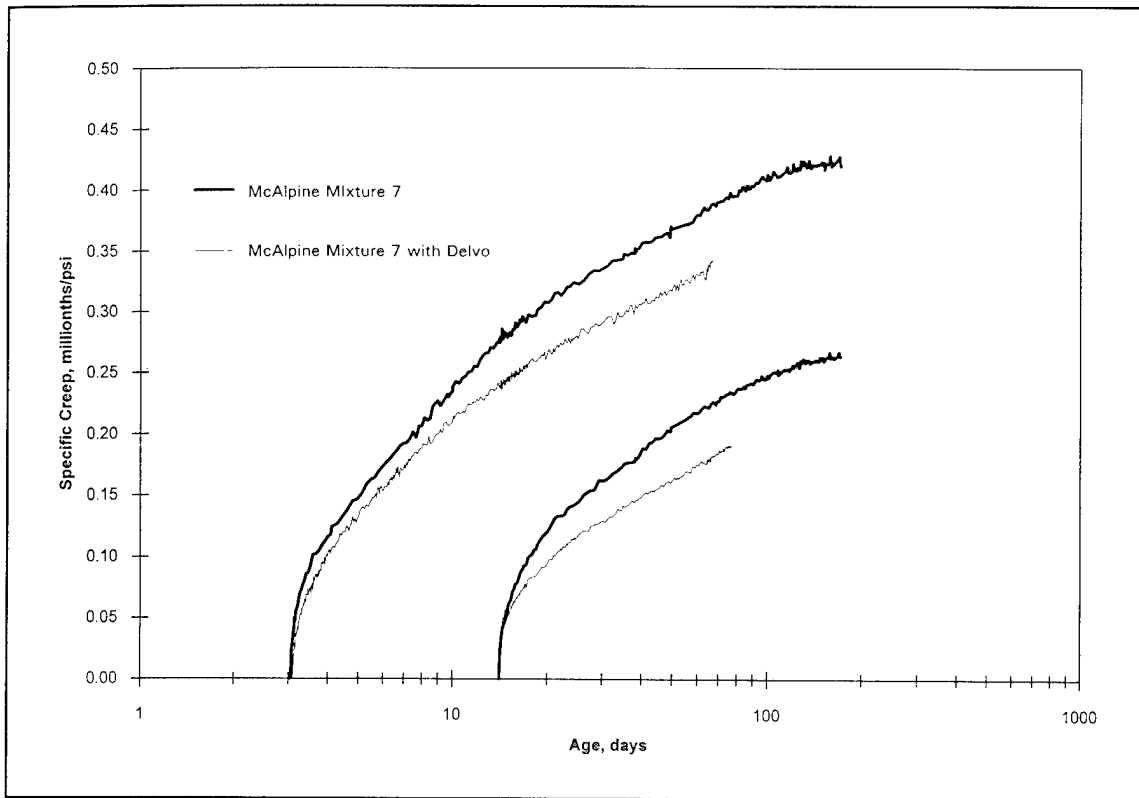
Figure 14. Specific creep test results of DELVO and McAlpine mass-concrete mixtures

Table 27 Seven-Day Ultimate Strain Capacity[1] Test Results			
Mixture	Modulus of Rupture, psi	Tension	Compression
DELVO	240	69	64
McAlpine	215	62	59
[1] Strain = millionths.			
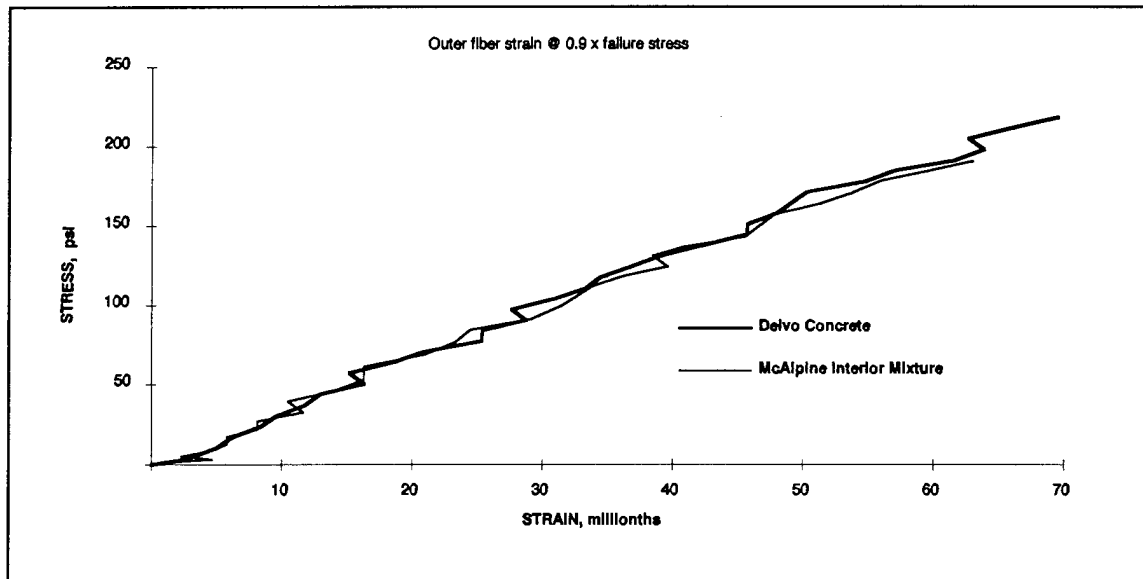
Figure 15. Seven-day tensile strain capacity results for DELVO and McAlpine mass concrete mixtures

The maximum anticipated allowable concrete placing temperature for the McAlpine concrete will be approximately 65° F. Both the DELVO and McAlpine laboratory mass-concrete mixtures closely approximated this maximum temperature. The adiabatic temperature-rise test results for the DELVO and McAlpine mixtures are shown in Figure 16. The adiabatic temperature rise of the DELVO mixture starts later than the McAlpine mixture as might be expected based upon the time-of-setting test results. However, it reaches that of the McAlpine mixture by 3-days age. The curves are generally similar thereafter and have achieved essentially the same temperature rise, approximately 47° F, at 27 days age. Once the cement hydration began in the DELVO mixture, it seemed to do so at a slightly faster rate than in the McAlpine mixture.

A comparison of the cracking potential between the DELVO and McAlpine mass-concrete mixtures seems to indicate that the DELVO might produce higher thermal stresses due to the primary temperature rise occurring later and over a shorter period of time, when the modulus of elasticity is higher and the creep is lower. The approximately 10-percent increase in the DELVO mixture tensile strain capacity would help compensate somewhat for this thermal stress increase. However, based upon the mechanical and thermal tests conducted in this investigation, it appears doubtful that the use of DELVO would lower the cracking potential of the mixture. A lower dose rate of DELVO stabilizer may have resulted in concrete that was more comparable to the reference concrete, and the cracking potential may have been reduced.
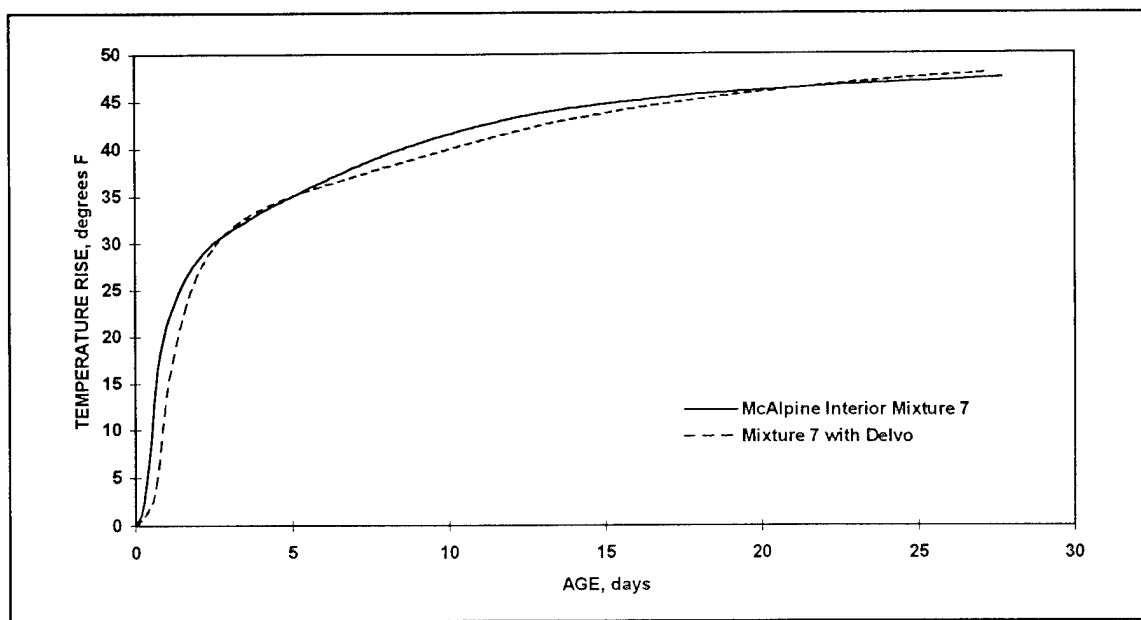
Figure 16. Adiabatic temperature rise of DELVO and McAlpine mass-concrete mixtures

Chapter 5   Use of DELVO in Lean Mass Concrete

6 Use of DELVO in Mass Roller-Compacted Concrete (RCC)

RCC Placement and Lift Joint Considerations

RCC is "concrete that, in its unhardened state, will support a roller while being compacted" (ACI 1994). Consequently, it has a lower water content in the fresh state than conventional mass concrete, which is consolidated by means of internal vibration. Tracked dozer equipment has proven to be best for spreading RCC since it is fast, is capable of creating sufficiently accurate lift thicknesses, and contributes to uniform consolidation. By careful spreading in thin layers, a dozer can provide some remixing of RCC and mitigate some segregation of coarse aggregate which results from dumping the material from trucks. Usually a 10-ton, steel-drum, vibratory roller intended for compaction of asphalt or granular base is used to consolidate RCC because its mass combined with its high frequency and low amplitude make it very effective for consolidating large volumes of fresh RCC relatively quickly. The consolidation of RCC should be accomplished as soon as possible after it is spread, especially in hot weather, to ensure that the specified density is achieved throughout the lift thickness.

Horizontal lift joints are inevitable in mass RCC because of the lift method of construction used to construct massive gravity sections. The USACE requires that lifts in mass RCC be constructed by spreading the RCC in approximately 6-in.-thick layers until the desired lift thickness is achieved (Headquarters, Department of the Army 1994b). The normal lift thickness ranges from 12 to 24 in. Consolidation with the vibratory roller is accomplished after all RCC comprising the lift is spread. The lift joint preparation currently required by the Corps after consolidation depends somewhat on the construction procedures and sequence being followed. In all cases, the underlying RCC lift surface must be constantly maintained in a moist condition commencing immediately following consolidation. If necessary, the lift joint should also be cleaned prior to placement of the next lift. The design of RCC structures where the Corps requires watertightness and bonding between lifts must require the application of bedding mortar over

the entire surface area between all lift placements (Headquarters, Department of the Army 1992). A bedding mortar is a high-slump, high-cement-content mixture that is used to increase bond between lift joints and to improve watertightness by filling any voids that may occur at the bottom of an RCC lift during placement and consolidation. The thickness of the bedding mortar must be sufficient to fill any voids at the bottom of the overlying lift. A separate concrete plant is typically required to produce the bedding mortar and spreading of the mortar, may be accomplished using a serrated rubber squeegee mounted on a small tractor or other vehicle.

Objectives of DELVO RCC Investigation

An abbreviated investigation was conducted at WES to evaluate the effects if any, of DELVO-stabilized RCC on joint bond strength, since the bond strength at compacted lift lines is more important to designers than the shear strength of the parent concrete. Bond strength was evaluated based upon direct-shear tests. If concrete treated with the DELVO stabilizer could be sufficiently retarded to allow placement of a succeeding lift of RCC without extensive joint cleanup and the use of bedding mortar, then potential savings in mass RCC construction might be realized on some types of RCC structures.

Scope of DELVO RCC Investigation

This investigation was conducted in two phases. The first phase involved evaluation of the effects of DELVO-Stabilizer at various dosage rates on the joint strength of RCC. This was a coordinated effort between WES and Master Builders and was accomplished by proportioning the RCC mixture of interest at several DELVO dosage rates, fabricating jointed 6- by 12-in. cylinders, and testing them for direct-shear strength. The second phase of the investigation involved construction of an approximate 80-yd^3 RCC test section in order to compare the direct-shear strength of DELVO lift joints with those bonded with bedding mortar.

RCC Materials and Mixtures

The cement used in the first phase of DELVO RCC investigation, CTD Serial No. 930020, met the requirements of ASTM C 150 (ASTM 1992c) Type II cement, including the optional 7-day heat-of-hydration requirement. The chemical and physical properties of the cement are given in Table 28. A Class F fly ash, assigned CTD Serial No. 910013, meeting the requirements of ASTM C 618 (ASTM 1992i) was also used in the mixtures. The chemical and physical properties of the fly ash are given in Table 29. Crushed-limestone coarse aggregates, CTD Serial Nos. CL-2 MG-2 and 920048, and the same natural siliceous fine aggregate as used in the mixtures cited in

Table 28
Test Results for Type II Cement (CTD Serial No. 930020) for First-Phase RCC Investigation

Chemical Determination, %	
SiO_2	21.8
Al_2O_3	4.2
Fe_2O_3	5.4
CaO	63.8
MgO	0.7
SO_3	2.0
Loss on ignition	0.7
Insoluble residue	0.21
Na_2O	0.16
K_2O	0.26
Alkalies-total as Na_2O	0.33
TiO_2	0.23
P_2O_5	0.18
C_3A	3
C_3S	50
C_2S	25
C_4AF	16
Physical Tests	
Heat of hydration, 7-day, cal/g	67
Surface area, m^2/kg (air permeability)	327
Autoclave expansion	0.07
Initial set, min (Gillmore)	205
Final set, min (Gillmore)	290
Air content, %	8
Compressive strength, 3-day, psi	1,910
Compressive strength, 7-day, psi	2,570
False set (final penetration), %	69

Table 29
**Test Results for Fly Ash (CTD Serial No. 910013) for First-Phase
RCC Investigation**

Chemical Determination, %	
SiO_2	55.6
Al_2O_3	28.8
Fe_2O_3	6.2
Sum	90.7
CaO	--
MgO	1.0
SO_3	0.4
Moisture content	0.1
Loss on ignition	4.3
Available alkalies (28 days)	0.88
Physical Tests	
Fineness (45 μm), % retained	12
Fineness variation, %	5
Water requirement, %	98
Density, Mg/m^3	2.26
Density variation, %	0
Autoclave expansion, %	-0.04
Pozzolanic activity w/lime, psi	1,480
Strength activity index, w/cement, 7-day, %	89
Strength activity index, w/cement, 28-day, %	--

Chapter 3 of this report were used in the RCC. In addition to the natural
siliceous fine aggregate, a manufactured-limestone dust, Serial No. 930357,
was also used to assist in filling voids between aggregate particles. The
gradings, absorptions, and bulk specific gravities for the coarse and fine
aggregates are given in Table 30.

The cement, CTD Serial No. 930338, used in the RCC mixture for the test
section met the requirements of ASTM Type II, except for the false-set
requirement. Additional testing of the cement in accordance with ASTM
C 359 (ASTM 1992e) indicated that false-set tendencies could be eliminated
with additional mixing; therefore, it was used. The chemical and physical
properties of the cement are given in Table 31. A Class F fly ash, CTD
Serial No. 930340, was used in the test section RCC mixture, and its chemical
and physical properties are given in Table 32. Two-size groups of crushed-
limestone coarse aggregate were used in the RCC for the test section. The
nominal maximum aggregate size was 37.5 mm. The same fine aggregates
used in the first stage of the DELVO RCC investigation were also used in the

Table 30
Aggregate Test Results for First-Phase RCC Mixture

Sieve Size	Cumulative Percent Finer			
	19.0 - 37.5 mm (CTD Serial No. CL-2 MG-2)	4.75 - 19.0 mm (CTD Serial No. 920048)	75 - 4.75 mm (CTD Serial No. 920024)	Limestone Dust (CTD Serial No. 930357)
50 mm (2 in.)	100			
37.5 mm (1-1/2 in.)	96			
25.0 mm (1 in.)	29	100		
19.0 mm (3/4 in.)	7	97		
12.5 mm (1/2 in.)	3	65		
9.5 mm (3/8 in.)	2	39		
4.75 mm (No. 4)	2	6	100	
2.36 mm (No. 8)		1	80	
1.18 mm (No. 16)			68	
600 μm (No. 30)			57	
300 μm (No. 50)			23	
150 μm (No. 100)			2	
75 μm (No. 200)			0	69[1]
Absorption, percent	0.3	0.2	0.8	--[2]
Bulk Specific Gravity	2.74	2.71	2.60	2.84

[1] Percent retained on 45 μm (No. 325) sieve = 48.
[2] -- indicates test was not conducted on this sample.

Table 31
Test Results for Type II Cement (CTD Serial No. 930338) in WES RCC Test Section

Chemical Determination, %	
SiO_2	21.1
Al_2O_3	3.8
Fe_2O_3	2.9
CaO	62.6
MgO	3.7
SO_3	3.0
Loss on ignition	1.2
Insoluble residue	0.15
Na_2O	0.09
K_2O	0.54
Alkalies-total as Na_2O	0.44
TiO_2	0.20
P_2O_5	0.10
C_3A	6
C_3S	54
C_2S	20
C_4AF	9
Physical Tests	
Heat of hydration, 7-day, cal/g	74
Surface area, m^2/kg (air permeability)	390
Autoclave expansion, %	0.06
Initial set, min. (Gillmore)	175
Final set, min. (Gillmore)	265
Air content, %	9
Compressive strength, 3-day, psi	3,080
Compressive strength, 7-day, psi	4,000
False set (final penetration), %	10

Table 32
Test Results for Fly Ash (CTD Serial No. 930340) Used in WES RCC Test Section

Chemical Determination, %	
SiO_2	53.2
Al_2O_3	25.8
Fe_2O_3	11.0
Sum	90.1
CaO	--
MgO	0.9
SO_3	0.5
Moisture content	0.1
Loss on ignition	1.6
Available alkalies (28 days)	--
Physical Tests	
Fineness (45 μm), % retained	4
Fineness variation, %	7
Water requirement, %	96
Density, Mg/m^3	2.30
Density variation, %	1
Autoclave expansion, %	-0.03
Pozzolanic activity w/lime, psi	920
Strength activity index, w/cement, 7-day, %	72
Strength activity index, w/cement, 28-day, %	--

test section RCC. The gradings, absorptions, and bulk specific gravities of the coarse aggregates are given in Table 33.

Forty percent, by volume, of cementitious materials used in the mixture for the first phase of the RCC investigation consisted of fly ash. Adjustments were made to the water content of the mixture to account for water-reducing capability of the DELVO Stabilizer. The mixture proportions are given in Table 34. Both the reference and DELVO-stabilized RCC mixtures used to construct the test section contained 40 percent, by volume, of fly ash. The DELVO-stabilized mixture had a water-reducing capability of approximately 6 percent based upon consistency tests conducted in accordance with CRD-C 53 (USACE 1949c), and this is reflected in its lower water content and w/c. The proportions for the mixtures are given in Table 35.

Table 33
Test Results for Aggregates Used in WES RCC Test Section

Sieve Size	Cumulative Percent Finer			
	19.0 - 37.5 mm (No Serial No.)	4.75 - 19.0 mm (No Serial No.)	75 - 4.75 mm (CTD Serial No. 920024)	Limestone Dust (CTD Serial No. 930357)
50 mm (2 in.)	100			
37.5 mm (1-1/2 in.)	96			
25.0 mm (1 in.)	49	100		
19.0 mm (3/4 in.)	17	96		
12.5 mm (1/2 in.)	3	69		
9.5 mm (3/8 in.)	1	48		
4.75 mm (No. 4)	1	12	100	
2.36 mm (No. 8)		2	80	
1.18 mm (No. 16)			68	
600 μm (No. 30)			57	
300 μm (No. 50)			23	
150 μm (No. 100)			2	
75 μm (No. 200)			0	69[1]
Absorption, %	0.7	0.7	0.8	--[2]
Bulk Specific Gravity	2.74	2.72	2.60	2.84

[1] In addition, 48 percent of the limestone dust was retained on the 45-μm (No. 325) sieve.
[2] -- indicates test was not conducted.

Table 34
RCC Mixture Proportions Used in First Phase

Saturated Surface-Dry Weight, lb/yd^3							
Portland Cement	Fly Ash	19.0 - 37.5 mm	4.75 - 19.0 mm	Fine Aggregate	Limestone Dust	Water	w/c
175	85	1,004	1,108	1,302	280	190	0.65

Table 35
RCC Test Section Mixture Proportions

Saturated Surface-Dry Weight, lb/yd^3							
Portland Cement	Fly Ash	19.0 - 37.5 mm	4.75 - 19.0 mm	Fine Aggregate	Limestone Dust	Water	w/c
Plain RCC Mixture							
195	95	1,107	1,011	1,186	300	211	0.65
DELVO RCC Mixture							
195	95	1,107	1,011	1,219	300	192[1]	0.61

[1] In addition to water, DELVO Stabilizer was added to this mixture at a dosage rate of 50 fl oz/100 lb of cement.

Testing of RCC Mixtures

During the first phase of the RCC investigation, two series of trial batches were produced, and jointed 6- by 12-in cylinders were molded to simulate RCC placed with varying DELVO Stabilizer dosage rates. During the first series of trial batches, eight joint conditions were evaluated for direct shear strength. A total of 48 cylinders were molded, six for each condition, and cured at 73 °F in a moist condition for approximately 90-days age. Generally, only three specimens representing each condition were tested for direct shear strength in accordance with applicable provisions of RTH 203 (USACE 1991). Cylinders were molded by filling the bottom half of the molds with the RCC mixture of interest and consolidating them on the Vebe vibrating table until paste was evident on the RCC surface. The top halves of the molds were then filled at the appropriate time with the mixture of interest and again fully consolidated on the Vebe vibrating table. Three inches was sawed off the top and bottom of the cylinders, leaving a total specimen length of approximately 6 in. Each specimen was grouted into specimen-retaining rings using a gypsum cement grout. A spacer was inserted into the rings at the joint location in order to avoid confining the joint with the grout. The specimen

was then placed into a pair of shear boxes (Figure 17), which were constructed so as to provide a means of applying a normal stress to the face of the specimen while applying a force to shear the specimen along a predetermined plane perpendicular to the vertical axis of the specimen. The shear boxes were sufficiently rigid to prevent their distortion during shearing, and the shearing device securely held the specimens in such a way that torque could not be applied to the specimen. The shear boxes assembled with the specimen were placed within a framework constructed so as to hold the boxes in proper position during testing. The framework included a pair of hardened stainless steel plates machined to accommodate roller bearings for minimizing friction of the moving shear box. The framework also included the capability of providing a submerging tank for tests in which maintaining specimen saturation is important to duplicate field conditions. The assembled shear boxes and framework are shown in Figure 18. Specimens tested in this investigation were submerged in water during shear testing. Normal stresses of 28, 56, and 112 psi were applied to the specimens within each set of three. The shear force was applied uniformly along one-half face of the specimen with the resultant applied shear force acting in the plane of shearing. The conditions represented by each set of three specimens molded from the first series of trial batches are presented in Table 36. In addition to the joint cylinders made for direct shear tests, 12 unjointed cylinders were molded for compressive strength. Four cylinders each were molded to represent plain RCC, DELVO-stabilized RCC containing 4-oz DELVO Stabilizer/100 lb of cement, and DELVO-stabilized RCC containing 64-oz DELVO Stabilizer/100 lb of cement. Cylinders were molded in accordance with ASTM C 1176 (ASTM 1992l).

A second trial batch series was produced approximately 6 months after the first in order to evaluate the use of DELVO Stabilizer in RCC in certain conditions not studied in the first trial batch series. Nine conditions were evaluated, and direct shear specimens were molded and tested in the same manner as those for the first series. The conditions represented by each set of three specimens molded from the second series of trial batches are presented in Table 33.

The RCC test section constructed at WES (Figure 19) consisted of four lifts of RCC, each approximately 40 ft long by 15 ft wide by 1 ft thick. Only one lift of the test section was dedicated to the DELVO RCC investigation. The remainder was evaluated as part of another research project being conducted by WES. The lift of RCC constructed for the DELVO investigation consisted of two sections, although both were placed at the same time. One-half of the lift, or approximately 20 ft in length, consisted of DELVO-stabilized RCC, while the remaining 20 ft consisted of plain RCC. Fifteen 1-yd^3 batches of RCC were batched in a semi-automatic batching plant and mixed in a 1-yd^3 capacity pugmill mixer located at WES. The RCC was transported to the placement site in an end-dump truck and spread using a dozer. Final consolidation was achieved using a 10-ton, single steel-drum vibratory roller. Following rolling, the lift was covered with moist burlap and plastic film. Tests for consistency, unit weight, and air content were

60
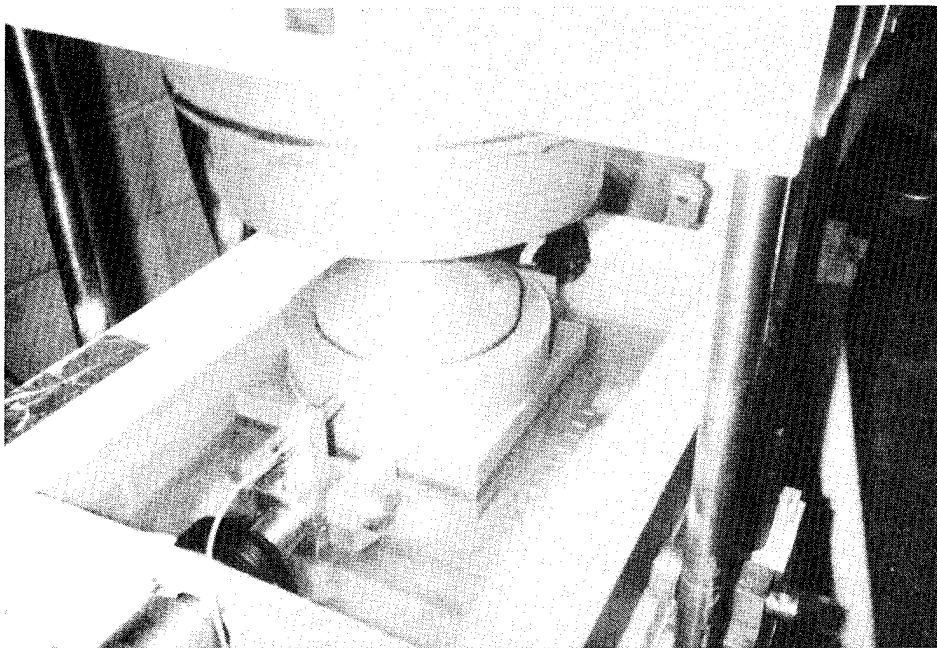
Figure 17. Specimen being placed into shear boxes
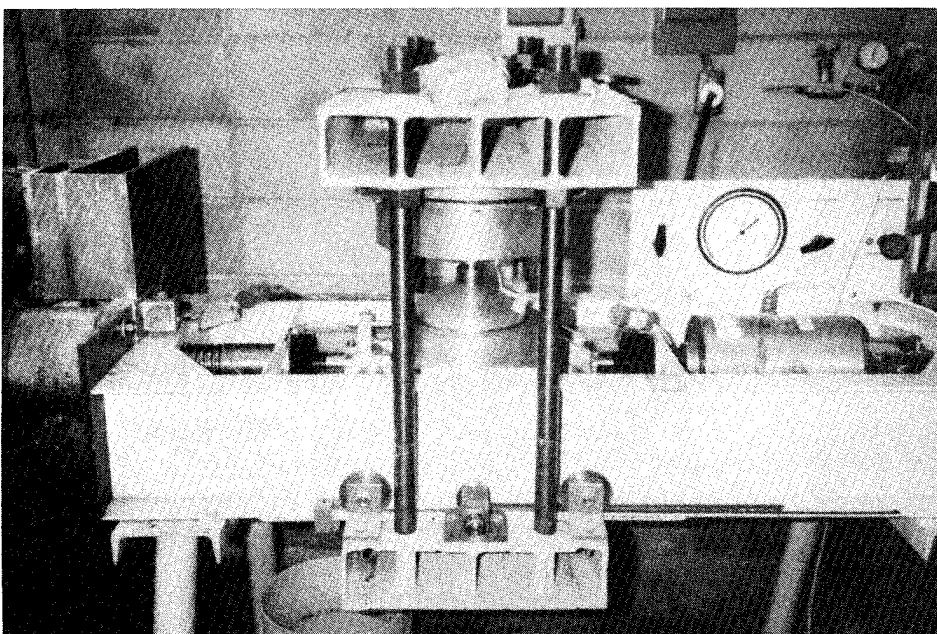
Figure 18. Assembled shear boxes and framework

Table 36
Joint Conditions Represented by Specimens from First Trial Batch Series

Batch No.	Bottom of Specimen	Top of Specimen
1-1	Plain RCC (aged 1 hr)	Plain RCC
1-2	DELVO @ 10 oz/100 lb of cement (aged 2 hr)	Plain RCC
1-3	DELVO @ 28 oz/100 lb of cement (aged 16 hr)	Plain RCC
1-4	DELVO @ 28 oz/100 lb of cement (aged 16 hr)	DELVO @ 10 oz/100 lb of cement
1-5	DELVO @ 48 oz/100 lb of cement (aged 24 hr)	Plain RCC
1-6	DELVO @ 48 oz/100 lb of cement (aged 24 hr)	DELVO @ 10 oz/100 lb of cement
1-7	Plain RCC (aged > 6 hr, hardened)	DELVO @ 48 oz/100 lb of cement
1-8	Plain RCC (aged > 6 hr, hardened)	DELVO @ 10 oz/100 lb of cement

Table 37
Joint Conditions Represented by Specimens from Second Trial Batch Series

Condition No.	Bottom of Specimen	Top of Specimen
2-1	DELVO @ 64 oz/100 lb of cement (aged 48 hr)	Plain RCC
2-2	DELVO @ 64 oz/100 lb of cement (aged 48 hr)	DELVO @ 10 oz/100 lb of cement
2-3	Plain RCC (aged > 24 hr, hardened)	Plain RCC
2-4	Plain RCC (aged > 24 hr, hardened)	Plain RCC with bedding mortar applied to joint
2-5	DELVO @ 48 oz/100 lb of cement (aged 24 hr)	Plain RCC
2-6	DELVO @ 48 oz/100 lb of cement (aged 24 hr)	DELVO @ 10 oz/100 lb of cement
2-7	DELVO @ 28 oz/100 lb of cement (aged 24 hr)	DELVO @ 10 oz/100 lb of cement
2-8	Plain RCC (aged 1 hr)	Plain RCC
2-9	Plain-RCC unjointed specimen	

Figure 19. RCC test section constructed at WES

conducted on selected batches of the fresh RCC. In addition, six 6- by 12-in. cylinders were molded from a sample taken from one of the plain-RCC batches and from one of the DELVO-stabilized batches.

Approximately 48 hr after placement of the combined plain and DELVO-stabilized RCC lift, a 1-ft-thick lift of RCC was placed on top. Prior to placement of this lift, the hardened plain-RCC surface was thoroughly cleaned by sweeping off all loose material and then washing. A layer of bedding mortar approximately 1/2 in. thick was then spread on the plain-RCC surface using a rubber squeegee. Nothing was done to the DELVO-stabilized RCC surface other than sweeping it clean and lightly misting it with water. Figure 20 shows a pile of RCC being spread onto the plain and DELVO-Stabilized lift surface. Bedding mortar is shown on the surface of a hardened RCC lift surface in the foreground of Figure 20. Six 6-in.-diam cores were taken from the test section approximately 90 days after construction and sawed into direct shear specimens. Three specimens, each representing the mortar joint, the DELVO-stabilized joint, and the intact DELVO-stabilized RCC, were tested for direct shear strength. Normal stresses of 28, 56, and 112 psi were applied to the specimens representing each joint condition.

Results of Tests from First-Phase Investigation

Members of Master Builders' staff visited WES on two occasions and were responsible for batching, mixing, and molding all test specimens made during

Figure 20. Bedding mortar on surface of hardened lift surface in foreground

the first phase of the RCC investigation. They also conducted consistency tests on samples from each batch in accordance with CRD-C 53 (USACE 1949c). Attempts were made to determine the initial times of setting of the RCC; however, the procedures described in ASTM C 403 (ASTM 1991g) were determined to be inappropriate for use with RCC due to the stiffness of the fresh mortar. The effects of DELVO Stabilizer on the extension of working time were evaluated by performing consistency tests periodically on RCC mixtures treated with varying dosage rates of the admixture. The desired Vebe consistency time was established by WES as 14 to 20 sec. The Vebe consistency time was monitored periodically from the time of mixing to the point at which the mixture would be judged unworkable, a Vebe consistency time of 25 sec. Figures 21-24 show the effects of DELVO Stabilizer on Vebe consistency time as a function of time from mixing. Figures 21 and 22 indicate that the Vebe consistency times of plain mixture and that treated with only 10 oz/100 lb continue to increase with time. The curves shown in Figures 23 and 24 are convex and seem to approach a constant Vebe consistency time before becoming unworkable. The Vebe consistency times of the mixtures which contained 64 and 128 oz/100 lb of cement did exceed the 25-sec limit; however, this may have been due to the water-reducing capability of the DELVO Stabilizer and the resulting lower w/c's of the mixtures. The effects of DELVO Stabilizer on compressive strength are shown in Table 38. Six 6- by 12-in. cylinders were tested at approximately 56-days age. Two cylinders each represented the plain RCC mixture and DELVO-stabilized RCC mixtures with 15 and 64 oz/100 lb of cement, respectively. The low dosage was comparable to that which might be used for an ASTM C 494 (ASTM 1993b) retarding admixture, and the higher

VEBE TIME BY TEST AGE

Delvo Dose = 0 oz/cwt
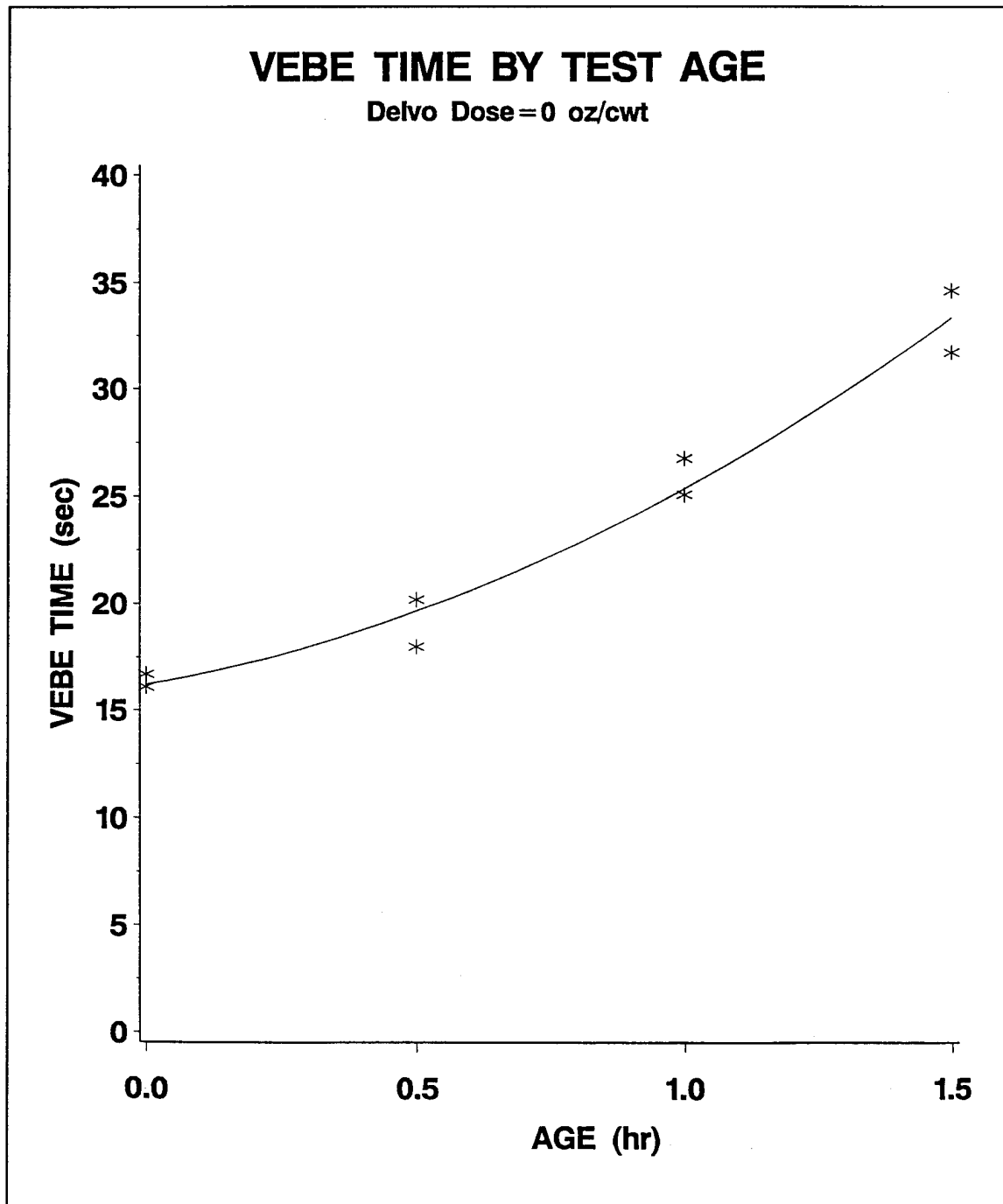
Figure 21. Effect of RCC age on Vebe consistency time
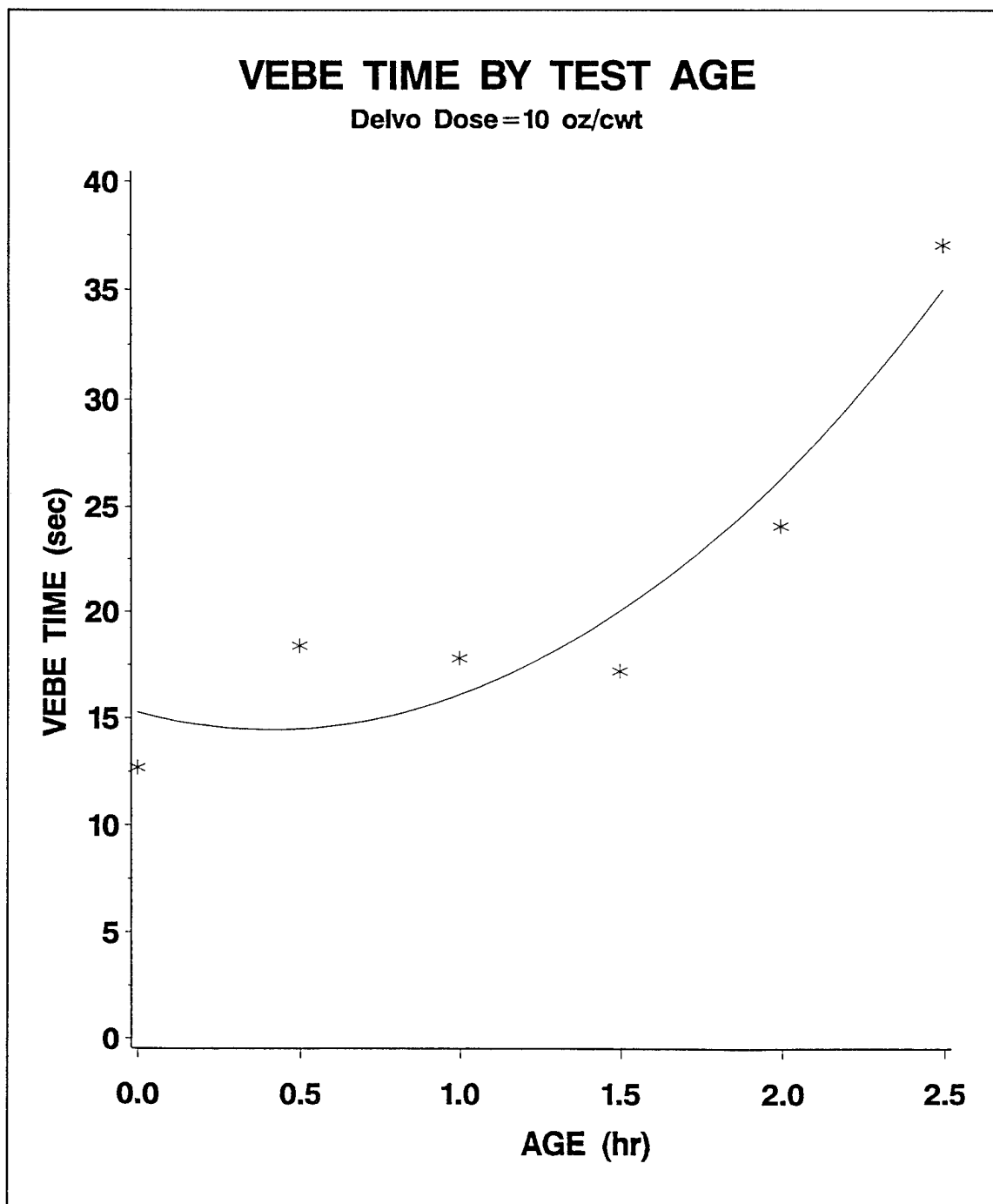
Figure 22. Effect of RCC age on Vebe consistency time, 10-oz DELVO stabilizer/100 lb of cement
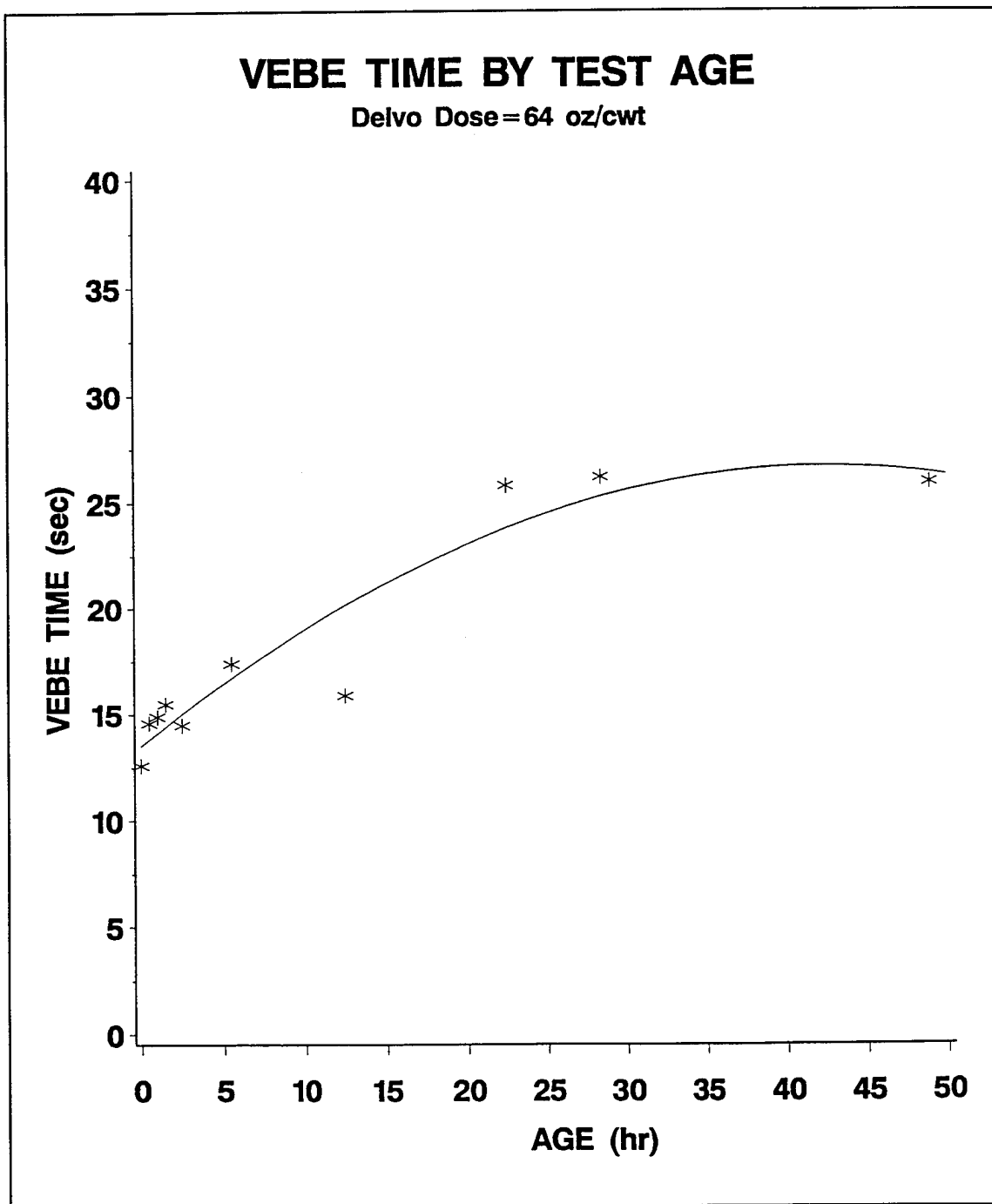
Figure 23. Effect of RCC age on Vebe consistency time, 64-oz DELVO stabilizer/100 lb of cement
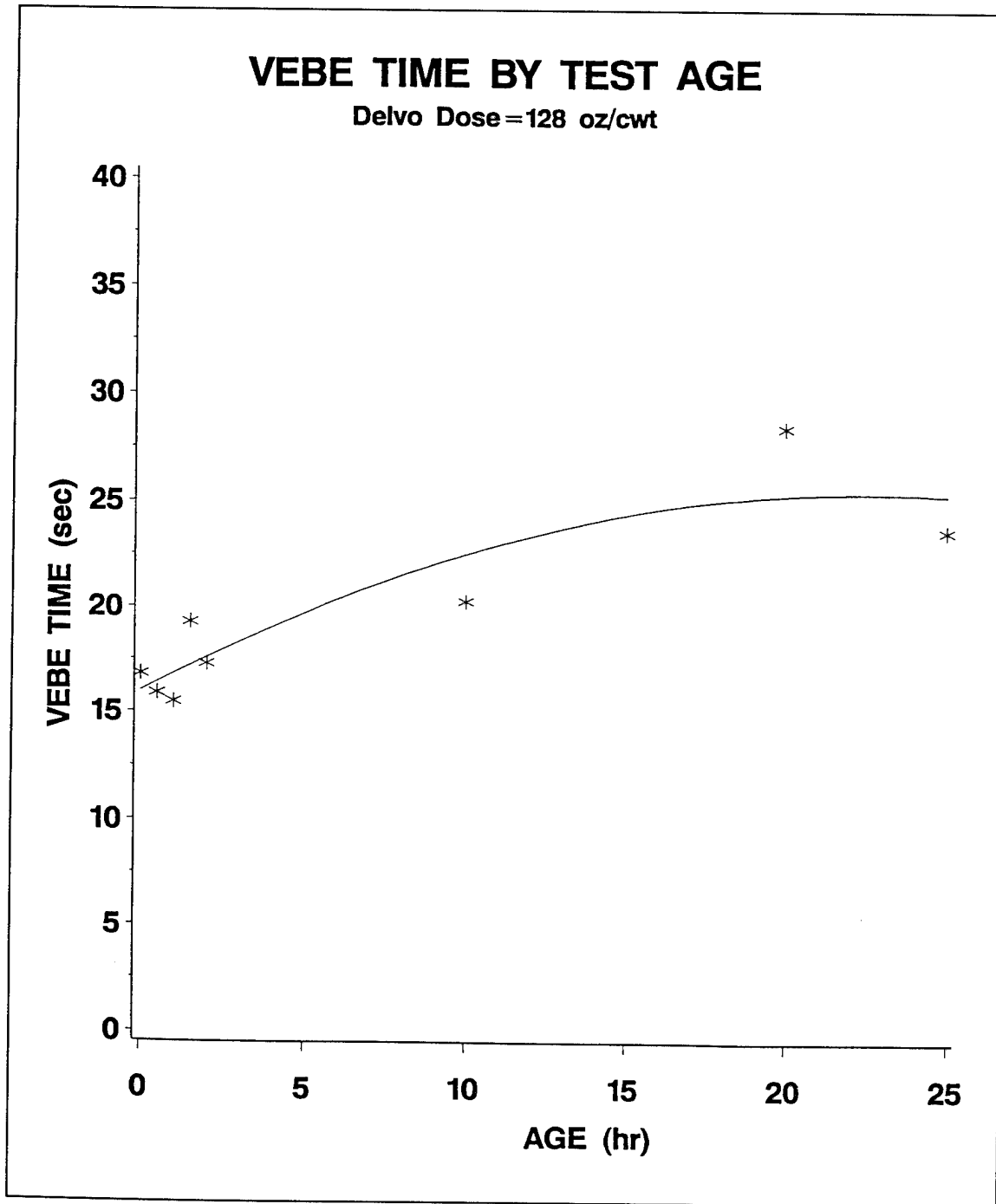
Figure 24. Effect of RCC age on Vebe consistency time, 128-oz DELVO stabilizer/100 lb of cement

Table 38
Compressive-Strength Test Results of First Phase RCC

Mixture	Compressive Strength, psi	Average Compressive Strength, psi
Reference	3,200 3,080	3,140
DELVO (4 oz/100 lb of cement)	3,240 3,270	3,255
DELVO (64 oz/100 lb of cement)	4,530 4,860	4,695

dosage was chosen to evaluate RCC with an extended retardation of a day or more. The higher strength of the concrete containing the higher DELVO dosage rate may be due to a lower w/c and more complete hydration.

Direct shear tests were conducted at WES by WES staff. Results of the direct shear tests on specimens from the first and second series of trial batches are given in Table 39. Failure envelopes for these groups of tests are shown in Figures C1-C17, Appendix C. The total shear strength of concrete can be determined from Coulomb's equation:

$$s = c + p * \tan \phi$$

where

s = unit shear stress, psi
c = unit cohesion, psi
p = unit normal stress, psi
ϕ = angle of internal friction, deg

At a given location within the structure, the resistance to sliding within the RCC section is dependent upon the cohesion, or unconfined, shear strength; the compressive stress on the potential failure plane; and the angle of internal friction of the concrete. The cohesion and angle of internal friction are material properties that may be evaluated by means of direct shear tests. It is convenient to categorize direct shear test results into four major groups. Group 1 considers plain RCC on top of plain RCC and consists of condition nos. 1-1, 2-3, 2-4, 2-8, and 2-9. Condition 2-9 represents an unjointed condition, but is put into Group 1 for the sake of comparison. Condition no. 2-8 had a correlation coefficient of less than 0.5 for the maximum shear stress on the normal stress and therefore is not considered in this discussion. The limited tests for this group seem to indicate that values for cohesion and ϕ may be expected to be high if the lower layer of plain RCC is fresh.

Table 39
Direct-Shear Test Results of Laboratory Molded Specimens

Joint Condition No.	Normal Stress, psi	Maximum Shear Stress, psi	Cohesion, psi	Internal Friction Angle
1-1	27	587		
	56	587	514	61°
	112	725		
1-2	27	737		
	56	802	694	60°
	112	885		
1-3	27	642		
	56	667	611	49°
	112	738		
1-4	27	688		
	56	658		
	56	741	681	15°
	112	711		
1-5	27	572		
	56	588	556	29°
	112	619		
1-6	27	583		
	56	683	542	63°
	112	759		
1-7	27	535		
	56	625	514	57°
	112	672		
1-8	27	613		
	56	660	597	38°
	112	684		

(Continued)

Table 39 (Concluded)

Joint Condition No.	Normal Stress, psi	Maximum Shear Stress, psi	Cohesion, psi	Internal Friction Angle
2-1	27			
	56		53	63°
	112			
2-2	27			
	56		78	75°
	112			
2-3	27			
	56		625	9°
	112			
2-4	27			
	56			
	56		635	44°
	112			
2-5	27			
	56		521	61°
	112			
2-6	27			
	56		593	21°
	112			
2-7	27			
	56		639	17°
	112			
2-8	27			
	56		552	7°
	112			
2-9				
			623	29°

Although the cohesion of condition no. 2-3 is high, the ϕ is only 9°. That is, once the unconfined shear strength was exceeded, relatively little additional shear strength was provided due to frictional resistance along the shear plane. The addition of bedding mortar to a hardened lower layer, as represented by condition no. 2-4, does not appreciably contribute to the cohesion but does improve the frictional resistance as indicated by the higher value of ϕ. Both the cohesion and ϕ of unjointed condition no. 2-9 are comparable to those of the jointed condition with bedding mortar. This is somewhat surprising but may be the result of very good consolidation of the upper layers of the jointed specimens.

Group 2 considers plain-RCC layers on top of DELVO-stabilized RCC layers. Results of tests on specimens representing conditions no. 1-2, 1-3, and 1-4 seem to indicate that both cohesion and ϕ are functions of the dosage rate of DELVO Stabilizer. Both the cohesion and ϕ decrease with increasing dosage rates of DELVO Stabilizer in the lower layers, which might lead one to believe that concrete containing DELVO had reduced friction resistance. However, it may be important to note that the lower layers not only contained varying DELVO Stabilizer dosage rates, but also were aged for different periods of time. The differences in cohesion and ϕ for this group may have had more to do with the fact that joint surfaces were sufficiently hardened to cause them in some cases to act as untreated cold joints. Condition no. 2-5 was intended to be the same as condition 1-5. However, although the cohesions are comparable, the ϕ of condition no. 2-5 is significantly higher than that of condition no. 1-3. This cannot be readily explained unless the joint surface of condition no. 2-5 was, in fact, significantly fresher than that of condition no. 1-3 at the time the upper layer of RCC was placed, or unless the joint surfaces of specimens representing condition no. 2-5 were appreciably rougher. Condition no. 2-1 represents a very high DELVO Stabilizer dosage rate in the lower layers of the specimens. The cohesion for this condition would seem to indicate that very little bond occurred between the upper and lower layers of the specimens.

The joint conditions considered in Group 3 include those resulting from upper and lower specimen layers of DELVO-stabilized RCC. Condition nos. 1-4 and 2-7 were intended to be replicates. For no readily apparent reason, the ϕ's for these joint conditions were very low. The cohesions for both conditions are high, indicating high unconfined shear strengths. Apparently, after shearing began along the joint, very little frictional resistance was encountered. Condition nos. 1-6 and 2-6 were also intended to be replicates. Although the cohesions for these are somewhat comparable, the values for ϕ are significantly different. Again, no apparent reason exists for this unless the lower joint surfaces of specimens representing condition no. 1-6 were fresher at the time concrete was placed on top of them. This may have allowed some embedding of coarse aggregate into the lower surface which would have increased friction resistance along the joint. The cohesion of condition 2-2 is low compared with the other conditions in this group. Both the cohesion and value for this condition compares favorably with those of condition no. 2-1, which also contained a large dosage of DELVO Stabilizer in the lower

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specimen layers. The lack of apparent layer bonding for the conditions represented by specimens containing high DELVO dosage rates is not obvious, but may be a result of cold joint surfaces in the lower layers. However, this does not readily explain the high ϕ values for these conditions.

Group 4 considers DELVO-stabilized RCC layers on top of plain RCC. The lower layers of plain RCC in specimens representing condition nos. 1-7 and 1-8 were allowed to harden before placement of the upper RCC layers. The moderately high cohesion and ϕ values for these conditions indicate relatively good bond and friction resistance between specimen layers, and in fact these shear parameters are comparable to those of the plain-RCC jointed specimens in which the lower layers were fresh. This seems unreasonable, and additional testing would be required to confirm these results.

Although molding and testing of laboratory RCC specimens may be helpful for evaluating certain properties, they may not necessarily always provide an accurate assessment of how the material will perform under actual field conditions. In some cases, differences in results of RCC test specimens molded in the laboratory may be more a function of specimen preparation, curing, and testing than changes in RCC properties. For this reason, cores were obtained from an RCC test section constructed at WES in order to evaluate the direct shear strength of lift joints. Two joint conditions were evaluated in the test section. One considered the case in which plain RCC was placed on top of a lift of DELVO-stabilized RCC approximately 48 hr after placement of the DELVO-stabilized RCC. This was intended to simulate a delay in placement as might occur in the field due to an equipment failure or the end of a working shift. The purpose was to maintain the RCC in a fresh state using the DELVO Stabilizer until fresh RCC could be spread and consolidated on top of it. The second condition simulated application of bedding mortar on top of a hardened lift surface, followed immediately by placement of another lift of RCC. This condition was intended to represent current practice often followed in treating lift surfaces prior to placement of fresh RCC. In addition to these two joint conditions, direct shear tests were conducted on the intact DELVO-stabilized RCC. This was done to serve as a comparison baseline for shear parameters of the two joint conditions. Variability in spreading and consolidating the RCC was minimized to the extent possible by constructing the lower lift of plain and DELVO-stabilized RCC at the same time and placing the upper lift over the plain and DELVO-stabilized lower lift at the same time. The results of the direct shear tests are given in Table 40. Failure envelopes for the three conditions are shown in Figure 25. The cohesion and ϕ's for these conditions indicate that, as might be expected, the cohesion of the intact concrete is higher than that of either joint condition. However, it is interesting to note that the cohesion of the DELVO-stabilized joint condition is approximately three times greater than that of the bedding mortar joint condition. While these conditions were each evaluated using only a single group of three tests, the results do appear to provide evidence that DELVO-stabilized RCC may indeed be a viable alternative in certain cases to treating lift surfaces with bedding mortar.

Table 40
Direct-Shear Test Results of Test Section Cores

Joint Condition No.	Normal Stress, psi	Maximum Shear Stress, psi	Cohesion, psi	Internal Friction Angle
Bedding Mortar	27	180		
	56	236	98	70°
	112	401		
DELVO-Stabilized	27	345		
	56	558	334	68°
	112	580		
Intact DELVO	27	651		
	56	700	540	73°
	112	923		
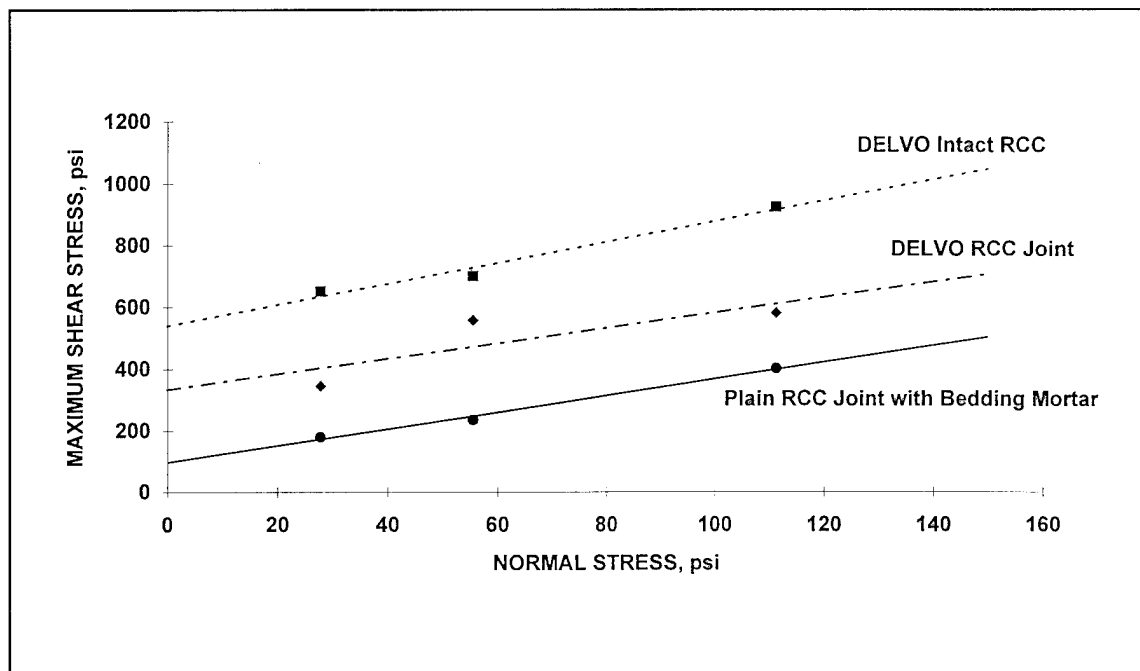
Figure 25. Direct-shear failure envelopes of cores taken from WES RCC test section

Chapter 6   Use of DELVO in Mass Roller-Compacted Concrete (RCC)

7 Simplification of the Use of DELVO Stabilizer

Background to Simplification

The DELVO System is a chemical system developed to control the time of setting portland-cement concrete. Concrete treated with DELVO Stabilizer remains unhardened for extended periods of time. Concrete returned from a jobsite can retain its unhardened character for a few hours or overnight if treated with DELVO Stabilizer. Procedures have been developed to use DELVO Stabilizer to substantially reduce the waste traditionally associated with washing out concrete trucks at the end of the day. When properly used, the re-use of wash water is now possible with the use of DELVO Stabilizer, thus reducing the need of disposing of either wash water or concrete at the end of the day. Stabilized concrete can then be incorporated into subsequent concrete loads to produce concrete with setting characteristics and hardened physical properties that match those of the original, untreated concrete.

DELVO Stabilizer has been successfully used for several years, but the novelty and a perceived complicated character have hindered the general acceptance of the product in the ready-mixed concrete industry. The DELVO User's Manual outlines procedures for more traditional applications:

a. Wash-water stabilization.

b. Long-haul stabilization of concrete for temperature control and slump retention.

c. Stabilization of returned concrete for same-day use.

d. Overnight stabilization of returned concrete for next-day use with an activator.

Simplification of the use of DELVO Stabilizer was defined in the DELVO CPAR agreement as follows: "Develop simplified procedures for the ready-mixed concrete industry which will enable accurate and concise dosage ranges of DELVO chemicals to be selected for a variety of applications." This

evolved to the development of a method that would allow simplified use of DELVO Stabilizer in the same-day application and reduce the time necessary to produce a chart of DELVO Stabilizer dosages for any concrete mixture. Simplification of the use of DELVO Stabilizer in the same-day application was regarded by most of the sales, marketing, and field personnel as a very difficult task. The procedures in use at the time were regarded by field personnel as having been simplified as much as was possible. Reducing the time necessary to produce DELVO dosage charts was regarded as an advantage to the customer and to Master Builders and would contribute to acceptance of the product throughout the industry. The use of DELVO Stabilizer in wash-water stabilization and the long-haul concrete applications were not regarded as complicated techniques and were not considered for simplification. These two applications are used to introduce new customers to DELVO Stabilizer in routine functions. As confidence in the system increases, a customer progresses to same-day stabilization and then to the overnight stabilization procedures, requiring more attention by the customer and the DELVO technologist.

The same-day and overnight stabilization procedures pose a technical challenge that does not exist in the wash-water and long-haul applications of DELVO Stabilizer, and it is the implementation of the same-day and overnight applications that complicates the use of the product. Once the dosage charts are established for a concrete mixture proportion, the use of DELVO Stabilizer by the customer is a straightforward application of a DELVO dosage chart to contend with the various combinations of mixture age and temperature. The procedures for all these applications have been established and are described in the DELVO System Implementation Guide.

Simplification of the use of DELVO Stabilizer would have been accomplished long ago if all cements responded similarly to the admixture or if all customers used the same cement. If this were the case, only one chart would suffice. In practice, a DELVO dosage chart is unique to concrete mixture proportions being produced by the customer. The perceived complexity of the product is derived from the sensitivity of the concrete induced by the cements used in concrete production, the mixture proportions of the concrete, and a unique DELVO dosage chart for each mixture a customer plans to treat in production. This portion of the CPAR project was intended to produce a method which would simplify the production of the DELVO dosage charts for the customer and to do so more quickly than was possible using traditional methods of evaluation and verification of charts.

Prior to this project, when a DELVO specialist first worked with a new customer, the process of concrete mixture evaluation, generation of a DELVO dosage chart, and the subsequent verification of the chart were required. The DELVO specialist usually had no knowledge of the time of setting or the response of a concrete mixture prior to his evaluation. The specialist's first activity was a concrete mixture evaluation in which he might be confronted with the logistical difficulties of acquiring the use of trucks necessary for a complete evaluation of the concrete mixture. This evaluation would provide

the first determination of the initial time of setting of the concrete with and without DELVO Stabilizer. An evaluation required the dedication of several trucks for aging and dosing the concrete mixture, usually an inconvenience to the customer. After a full day of evaluation, the following evening, and night, screened mortar samples produced by the evaluation were monitored for initial time of setting of the treated concrete for the same-day and overnight applications. The next morning, the DELVO specialist would have enough information to produce a DELVO dosage chart which would be verified by monitoring the times of setting of the mixtures for another night. The verification also demanded access to the customer's trucks for aging and dosing of the mixtures. Evaluation and verification required at least 2 days at any one site by the DELVO specialist and required the availability of the customer's equipment for both days' activities.

It was expected that enthusiasm of the sales force and the customers for the product would be improved if the "inconvenient" features of an evaluation could be reduced or eliminated. By reducing the time necessary for an evaluation and verification of a DELVO dosage chart, more effective use of the DELVO technologist's time would be realized as well as a reduction of the use of a customer's equipment.

At the beginning of this project, the outcome of simplifying the use of DELVO Stabilizer was envisioned as a nomograph that would include all the factors in unhardened concrete that affect the DELVO dosage rate. Such a nomograph could be used to generate a chart similar to the standard DELVO dosage charts. The production of a single nomograph was abandoned because of the variable conditions and materials that exist for any ready-mixed concrete producer. Experienced DELVO specialists recognized that individual cements behaved in "unpredictable" ways. This was thought to have a confounding effect on simplifying the determination of DELVO Stabilizer dosages for any one concrete mixture. It was necessary to understand the sources of this behavior, and a means was needed to anticipate the changes induced by the specific cements used. A computer program was believed to provide more flexibility to the DELVO specialist and eliminate sources of error which could be introduced by improper use of a nomograph.

Simplification of the use of DELVO Stabilizer was accomplished by means of a computer program written for Microsoft EXCEL™, commercial spreadsheet software. The DELVO Chart Generator program was based on field data that were analyzed by standard, multiple regression analysis to relate a set of predictor variables to a desired response. In this case, the response was the DELVO Stabilizer dosage. The production of this program required specific data that were not immediately available. Much time was spent in determining what was needed and in acquiring relevant information. Ultimately, statistical analysis of laboratory and field data resulted in the development of a computer program that eliminated the need for preliminary evaluation of concrete mixture proportions, simplifying the use of DELVO Stabilizer in the same-day and overnight applications.

If the customer can provide basic information to implement the DELVO Chart Generator, the new method eliminates the need for the traditional first-day evaluation. To realize the advantages of the computer program, the new method requires specific knowledge of the initial time of setting of the mixture without DELVO Stabilizer at a known temperature as well as other details of the concrete mixture such as the presence of admixtures or fly ash. Before arriving at a jobsite for verification of charts, the DELVO technologist will have entered the data into the DELVO chart generator, installed on a laptop computer. This will have generated a complete set of DELVO dosage charts for verification. By providing this information to the DELVO specialist, the customer and the specialist save time and enhance productivity by eliminating a full day of evaluating a mixture at the customer's location. The DELVO specialist must only verify or refine the previously generated charts, saving at least one sleepless night monitoring the mixtures.

The program provides a printout of the DELVO dosage chart, which documents the input information, the corrections to the chart determined by verification, and the final chart used by the customer in the production of the specific concrete mixture tested. The verified, printed charts will be given to the customer for his use. These charts are similar to those used previously with the exception that the generation of these charts requires less time and equipment to produce.

The First Database

A database was produced for this portion of the study prior to the formal beginning of the project. The database was a collection of DELVO dosage charts that had been collected from the years before the DELVO CPAR project was initiated. After the database had been compiled, statistical analysis was employed to rank the cements used in the concretes based on the DELVO Stabilizer dosage rates indicated in each chart. This ranking was the first attempt at characterizing the "reactivity." It was determined that the database was missing key information that could have simplified the use of DELVO in ready-mixed concrete.

The Florida Database

Early in this project, a Master Builders DELVO technologist indicated that he was developing a database of cements and DELVO Stabilizer dosage charts for concretes commonly used in Florida. The database included times of setting with and without DELVO Stabilizer with mixtures that predominantly contained fly ash and admixtures. A database was used to produce a computer program which generated DELVO dosage charts for same-day and overnight stabilization from the field evaluation data. Although such a program would not eliminate the need for evaluation, it was believed to be a step toward simplification because the data included times of initial setting for

all the concrete mixtures with and without DELVO Stabilizer. This database was the most complete set of concrete mixture data available, but the majority of the concrete mixtures contained fly ash or retarding admixtures or both. Because of this, it was initially regarded as insufficient to describe concretes that contained only DELVO Stabilizer. The evaluation data from this database were incorporated into the DELVO Chart Generator computer program.

The DELVO Chart Generator program is based on evaluations of concrete mixtures made with cements specific to the Florida region, but further investigations were made to determine the applicability of that database to regions, cements, and other mixture proportions. Other cements and verified DELVO dosage charts were requested to determine if laboratory testing along could be used to anticipate concrete mixtures that would exhibit anomalous DELVO stabilizer dose rates.

To isolate the DELVO Stabilizer effect and to determine if composition or other physical properties could be related to the dosage rates required of a specific cement, laboratory testing of cement and concrete was considered essential before simplification could be accomplished.

Calorimetry and Cement Testing

Laboratory testing of cements and mortars was done to determine if differences in composition or physical properties could be used to anticipate differences in required DELVO stabilizer dose rates. This testing was expected to isolate the effect of DELVO stabilizer in concrete. Laboratory testing of portland cements was conducted to isolate the DELVO Stabilizer effect.

Calorimetry is the measurement of heat of reaction produced by hydrating portland-cement pastes with time. These tests were used to determine if any differences in the time of setting could be related to other laboratory measurable parameters of the cement.

The thermogravimetric analyses (TGA) of cement pastes from these calorimetry studies measured small changes in mass as the hydrated, hardened cement pastes from the calorimetric studies were heated. This would indicate possible compositional differences between the cements as influenced by the presence of DELVO Stabilizer and dosage rate. The results of TGA testing of cement pastes indicated no detectable differences between the pastes made with or without DELVO Stabilizer and were discontinued.

These studies were made to determine the influence of cement phase composition, fineness, and other properties on DELVO Stabilizer dosage rate. It was suspected that air-permeability fineness could be a predictor of the DELVO Stabilizer dosage rate.

Nine small samples of portland cement were submitted for microscopical examination, X-ray powder diffractometry, fineness determination, and calorimetry. DELVO dosage charts were reported to have been developed for concrete containing each of these cements, but the charts were not immediately available. With the exception of calorimetry, all other laboratory testing was completed, and preliminary statistical analysis of the fineness information began. The analysis suggested no usable correlation with submitted charts. Because of the lack of initial time of setting data, no comparison of cements was possible. The quantities of the cements submitted for this series of tests were too small to complete mortar tests of the cements.

Early calorimetry tested the response of the cements when DELVO was added with the mixing water. In this sense, the testing more accurately simulated the long-haul stabilization application. Later, the calorimetry procedure was modified to delay the addition of DELVO Stabilizer to more accurately simulate the aging and stabilization of the same-day and overnight application. Calorimetry, however, was abandoned prior to the implementation of this modification.

Cement fineness appeared to influence the initial time of setting and the DELVO dosage rate of the pastes studied. Fine cements were characterized by shorter initial times of setting. After consideration of the problem, reactivity was used to describe the intrinsic characteristics of an individual cement affecting the initial time of setting. A more reactive cement was characterized by a relatively shorter initial time of setting.

Cement and Mortar Testing and Reactivity

For this study, the generalized response of any one cement to its hydrating environment in concrete, is termed reactivity. The term is used to compare the response of two or more cements in mortars or concretes. Prior to this project, DELVO specialists described a specific cement as "hot" or "cool." A "hot" cement characteristically exhibited short initial times of setting and relatively high DELVO Stabilizer dosage rates. Once it was realized from the statistical analysis of the first database that the data were incomplete, a loose ranking of the reactivity of the individual cement as low, medium, high, or very high as derived from the required DELVO Stabilizer dosages indicated in the dosage charts. Cement reactivity was found to be a feature that should be modeled by the response of their mortars with and without DELVO Stabilizer and at varying temperatures. It was recognized that a more effective means of characterizing reactivity was needed, but the sources of the reactivity of a cement were not well understood. Fineness and cement clinker phase composition were believed to be important contributors to that feature.

A three-part plan was implemented to study the initial times of setting indicated by reactivity of cements as influenced by the fineness of the cement. Phase I examined the relationship between the initial time of setting of

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concrete, temperature, and cement reactivity in mortars. Phase II was the collection and modeling of chart data collected from the field. Phase III was testing and refinement of the empirical models.

As part of Phase I, a list of factors known to affect the time of setting of DELVO-stabilized concrete included the following:

a. Temperature of the concrete to be stabilized.

b. Ambient temperature.

c. Age of the concrete mixture to be stabilized.

d. Volume of concrete to be stabilized.

c. The ratio of old concrete to fresh concrete (for overnight stabilization).

e. Cement content of concrete.

f. Water/cement ratio.

g. Cement clinker phase composition.

h. Cement fineness.

i. Cement alkali content.

j. Presence of ground granulated blast-furnace slag or pozzolans such as fly ash.

k. Presence of chemical admixtures in the mixture other than DELVO.

Because the DELVO dosage rate is also a function of the initial time of setting of a mortar or concrete, these factors were incorporated into a statistical model that could be used to predict the DELVO dosage. It was on these factors that the ultimate simplification was based.

Phase I

The first step was to collect cements of different reactivity and to determine if fineness and cement clinker phase composition are major predictors of the different reactivities. Cements from the same clinker but of different air-permeability fineness were collected, as well as cements with differing clinker phase composition. These cements were tested in mortars at temperatures of 50 °F, 70 °F, and 90 °F. The shape of the curve relating temperature to initial times of setting of the mortar was then observed. It was expected that the curves would approximate the rule of thumb that for every 10 °C (18 °F) reduction in temperature, the reaction time doubles. For

example, if the initial time of setting of concrete at 68 °F was 6 hr, it would be possible to assume the initial time of setting of concrete at 50 °F and 86 °F would be 12 hr and 3 hr, respectively.

Variation of this rule was expected for cements having different fineness and phase composition. In Phase I, the plan was to classify the cements to account for changing initial times of setting as influenced by temperature. Once a cement was classified, the initial time of setting for one temperature was determined, and the theoretical initial time of setting could be predicted for all temperatures within the 45 °F to 95 °F range as indicated in a DELVO Dosage chart Figure 26.

SAME DAY DOSAGE CHART, oz./cwt.

Age (hours)

Temperature	>1-1.5	>1.5-2	>2-2.50	>2.5-3	>3-3.5
100-109					
90-99					
80-89					
70-79					
60-69					
50-59					

Figure 26. Example of time and temperature parameters for same-day stabilization dosage chart

Laboratory determinations of the initial time of setting of mortars at 50°, 70°, and 90 °F with and without DELVO stabilizer were begun. To test the influence of fineness on the reactivity of the cements and DELVO Stabilizer dosage demands, 10 cements were selected for study. There were five cement groups (brands). Each group consisted of two cements produced from the same clinker, but each cement was of different fineness, and these were differentiated as Type I and Type III cement. By x-ray powder diffractometry, no significant differences in clinker phase composition were noted between cements within each group. As expected, the sulfate content and fineness of the Type III cements appeared higher than those of the Type I cements for each group.

Within each group, the most significant difference was believed to be the fineness between the Types I and III cements. Differences in the response of the mortars among the groups of cements could be related to the phase composition differences or compositional subtleties if they existed. Through consideration of the initial times of setting of the mixtures, the relative response of a cement to DELVO Stabilizer was studied. This showed the

influence of fineness of the cement on the DELVO Stabilizer dose rate without being confounded by clinker phase composition effects between cement brands. The cements were tested in mortars with and without DELVO Stabilizer, at standardized dosages of DELVO Stabilizer, and at various ages at the time of stabilization.

By this time, it was suspected that the reactivity of the cement in concrete could be expressed as an empirical physical feature of the cement, mortar, or concrete. That feature is the initial time of setting at a specific temperature. Various concrete mixture proportion features such as the presence of fly ash or chemical admixtures or environmental factors such as mixture temperature could influence that time of setting by reducing or extending the initial time of setting.

The 10 cement samples collected for the mortar studies were sent to an outside laboratory for particle-size analyses. These were used to show the differences in surface area as indicated by the sedigraph, by air-permeability fineness (ASTM C 204 1992d), and by the material passing the 45-μm sieve (ASTM C 430 1992f). This information was used in statistical analyses of the cements in mortars, at different temperatures, at different ages of stabilization, and at different dosages of DELVO Stabilizer.

Phase II

The next step was to collect chart data from various customers. It was expected that this information would necessarily be collected in the field at customers' facilities. Based on findings in Phase I, it was expected that every cement could be placed into its proper classification group. The initial time of setting was to be determined with a record of concrete temperature, and this would be compared to the chart information or evaluation information. All the dosages listed on the charts would necessarily be assumed to work for the customer.

Each chart developed for analysis was to contain the following information:

a. Cement name.

b. Classification group (from the work performed in Phase I).

c. Concrete temperature from the evaluation.

d. Initial time of setting for the customer's mixture at concrete temperature.

e. DELVO Stabilizer application (same-day or overnight).

f. DELVO Stabilizer dosage for each temperature and age combination (a completed chart).

Statistical analysis for this phase would predict initial times of setting for all temperatures based upon the initial time of setting and the classification group. From the initial time of setting information, the DELVO Stabilizer dosage could be predicted for a specific application, temperature, age, and classification group. If the initial time of setting was closely predicted, a good estimate for the proper DELVO Stabilizer dosage could be made. The correct DELVO Stabilizer dosage for a given temperature would be a function of age of the mixture from batching time and the initial time of setting of the mixture at a specific temperature. In other words, the DELVO Stabilizer dosage would be a function of how close a mixture is to its theoretical initial time of setting relative to the age of the concrete at the time of stabilization.

It was expected that the information for this portion of the study could be obtained from the field. After that time, it was determined that the data in the Florida database were the most complete set of information available and provided the best opportunity to develop an effective model. A new program of collecting field data was judged to be too time consuming and unnecessary because the Florida database was taken from the field. The concrete evaluation data from Florida appeared to be complete enough to begin studies relating dosage rates to times of setting.

Phase III

The last phase would be testing and refining the models. It is possible to incur error from the field testing and from both predictive models; therefore, it is important to monitor the success of the models in practice. It was essential to identify the situations where the predictions were not close to the proper values. In several cases, the data from traditional evaluations were compared to the charts produced from the DELVO Chart Generator from various regions of the United States. In most cases, the results of the first approximations were very close, and a verification facility within the program was expected to provide the necessary corrections to the chart. This testing has been occurring in the field during the project.

Computer Modeling

Statistical analysis of results of mortar testing confirmed that temperature and age of the mixture at the time of stabilization are major factors that affect the initial time of setting and, consequently, the dosage rate of DELVO Stabilizer. These factors were always considered in the development of DELVO Stabilizer dosage charts. Cement fineness was also found by statistical analysis to be an important factor affecting the initial time of setting of the mortars. Information regarding the methods of determining the particle size was also compared in these studies. Further statistical analysis of the mortar time of setting data suggested that clinker phase composition of the cement may be of less importance to time of setting of a stabilized mortar than was

previously believed. An early computer model was based on the assumption that the times of setting of mortars are predictable with knowledge of the volume, temperature, age of the mixture at stabilization, and fineness of the cement.

Particle-size distribution and surface area of the cements by sedigraph, the surface area determined by the air-permeability apparatus (ASTM C 204 (ASTM 1992d)), and the fineness as determined by the cement passing the 45-μm (No. 325) sieve (ASTM C 430 (ASTM 1992f)) were gathered on the 10 cements used in the mortar studies. These methods of describing fineness were found by statistical analysis to be highly correlated. The mortar studies indicated that the response of each cement to DELVO is unique and that the finer cements exhibited higher reactivity than did the coarser cements. It was observed that the laboratory mortars produced for these studies typically exhibited shorter times of setting than would be expected of concrete in the field. From the mortar testing, it was observed that the initial time of setting of a mixture may be predictable at a specific temperature. If the model can be used to predict the initial time of setting of mortars, then it should be possible to predict the DELVO Stabilizer dosage.

Statistical analysis of the Florida database began to relate initial time of setting to the DELVO dosage rate, and the influence of temperature and fineness on the initial time of setting of specific cements to DELVO Stabilizer was better understood. From the evaluation of data in the Florida database, a computer program could be written that would predict a theoretical initial time of setting and from that, a DELVO Stabilizer dosage rate.

Although the field data from Florida were the most complete available at the time, the documented mixtures usually contained a retarding admixture and fly ash. Early in the study, the presence of any chemical admixture, fly ash, or slag in a mixture would have been regarded as a problem because these prevented the isolation of the effect of DELVO Stabilizer on any one mixture. From the mortar testing, an estimate of the theoretical time of setting at the various temperatures within a DELVO dosage chart was possible. It was now possible to develop a computer model that accounted for the initial time of setting of a mortar or concrete mixture and to determine the theoretical time of setting of concrete mixtures at specific combinations of temperatures and ages expressed in the full DELVO dosage chart. By expanding the computer program, a theoretical time of setting of a specific mortar or concrete mixture could be predicted if the one initial time of setting at a specific temperature were known. Knowing the theoretical initial time of setting of a mixture for all temperature conditions in the DELVO chart, the ratio of the theoretical time of setting of the mixture at different ages could then be computed. The Florida evaluation data and charts could then be employed to relate the ratio of absolute age of a concrete mixture to the DELVO Stabilizer dosage which stabilized the mixtures.

Figure 27 shows the Florida field evaluation data plotted as the ratio of age to theoretical time of setting versus the square root of the DELVO Stabilizer
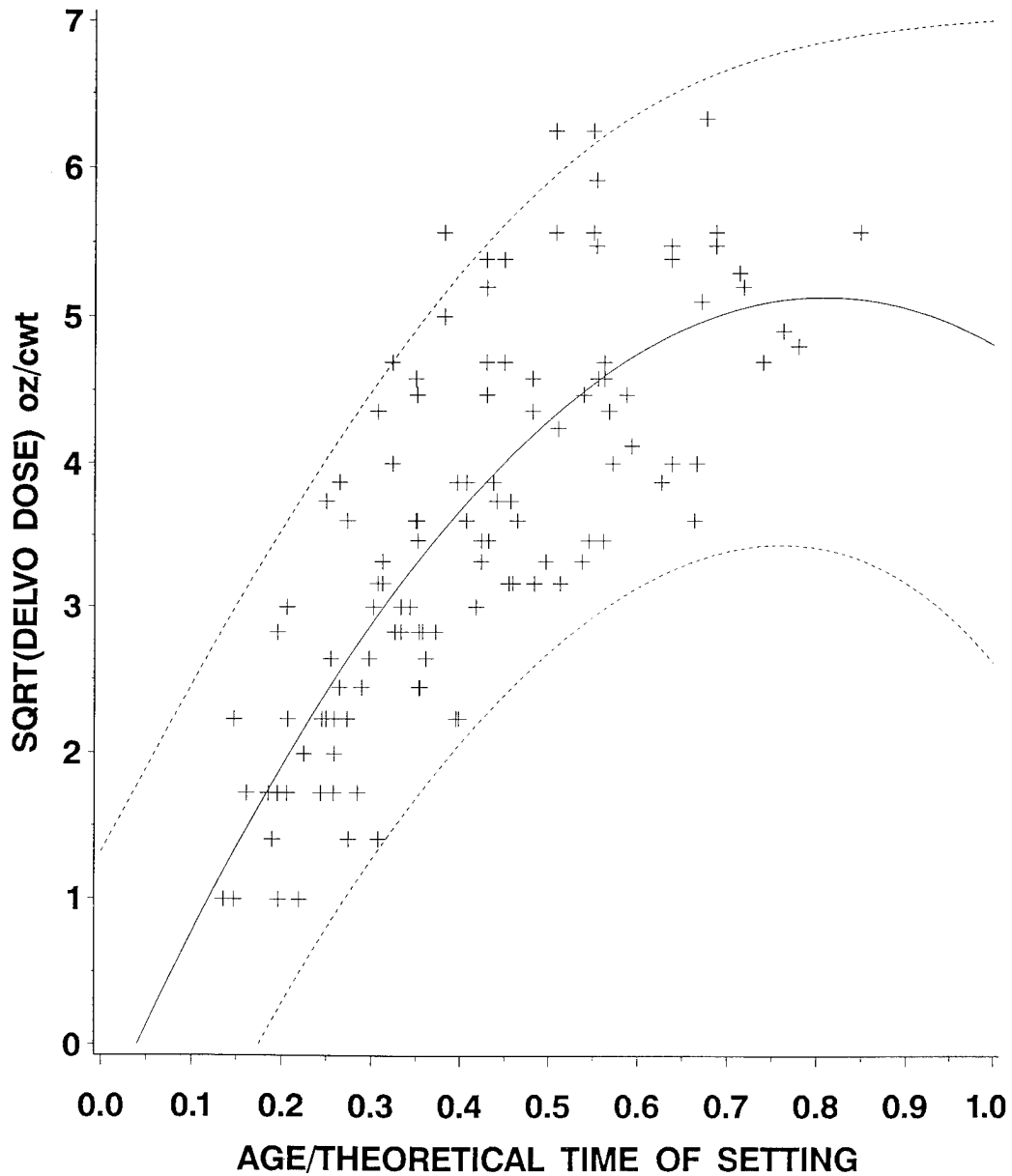
Figure 27. Results of time-of-setting tests compiled conducted on concrete produced in
Florida and compiled by Master Builders

dosage rate. The regression curve is the solid line in the field of data, with the 95-percent predictor limits shown as dotted lines above and below the regression line. For any combination of the ratio of mixture age to theoretical time of setting, the first approximation of the DELVO dosage necessary to stabilize the mixture for the same-day application is expressed as the square root of the dosage. The data could now be used to establish a computer program that could predict a theoretical initial time of setting. The ratio of absolute mixture age to theoretical time of setting is calculated and from that, the DELVO Stabilizer dosage rate is predicted from the regression. Correction for the presence of retarding admixtures and fly ash is also incorporated into the computer program to refine the determined DELVO Stabilizer dosage rate.

In October 1993, the first computer program based on Florida field data was completed. The program generated DELVO dosage charts for the same-day application from a few prompted inputs. The program appeared to present a good first approximation of DELVO Stabilizer dosage rates. A few refinements were made with an added provision in the program to adjust the charts after verification of the chart.

Copies of the computer program were sent to the field for evaluation by sales representatives, and their comments were expected. The limited access of the sales representatives to laptop computers delayed the implementation of the program in the field; thus, no comments were received on the success of the program in predicting DELVO Stabilizer dosage rates.

In January and February 1994, programming of the DELVO dosage chart generator was extended to include an algorithm based on the Florida database, which permitted the production of overnight DELVO dosage charts from the same-day DELVO dosage chart. Refinement of the program continues.

It should be noted that the data used to derive the DELVO dosage model were produced from charts created by DELVO technologists who had worked with the product for many years before this CPAR project. Before field testing of the concrete, the only basis of comparison or measure of success of the DELVO Stabilizer Chart Generator was the comparison of the program-generated chart with the charts produced by the DELVO specialists. When charts derived from field evaluations are compared with the computer-generated charts, the charts have been in close agreement.

The DELVO dosage chart generator has been integrated into the training activities of sales representatives. If the verification data are made available, refinement can be integrated into the program as necessary as extensions of the database.

It is recognized that different environmental conditions and regional differences in cement production may influence the dosage of DELVO Stabilizer. Results to date indicate that the program provides good estimation

of DELVO Stabilizer dosage that would necessarily be verified regardless of the method used to generate the chart.

Tools of Simplification

Several tools are suggested for the simplification of the use of DELVO Stabilizer in practice. These include the following:

a. A laptop computer that allows the DELVO specialist access to the DELVO Chart Generator. The availability of a computer is essential to the use of the DELVO Chart Generator.

b. The DELVO Chart Generator to automatically generate a dosage chart on the basis of prompted inputs,

c. A thermal data logger to monitor thermal history and times of setting of concrete mixtures in chart verification,

d. A noncontact infrared pyrometer to more conveniently measure the temperature of returning loads of concrete.

DELVO Chart Generator

The key to the simplification of the DELVO stabilization procedure is the DELVO Chart Generator for the same-day and overnight applications. The DELVO Chart Generator is a computer program that generates DELVO dosage charts from prompted inputs of mixture information which should be available to the DELVO specialist before visiting a new account. The program makes the use of DELVO stabilizer more convenient to the DELVO specialist without substantially impacting the customer and his equipment because the initial evaluation of a concrete mixture is not necessary to generate the chart. The use of the program will require the availability of a computer. Ideally, a laptop computer with the program installed would be most convenient to the specialist onsite. Regardless of the method used to generate DELVO dosage charts, all charts must be verified.

Thermal data logger

A battery-powered, thermal data logger was used to relate the initial time of setting of mortars, as determined by the penetrometer, to the thermal history of the sample. In the laboratory, this instrument was found useful in the monitoring of the initial time of setting of mortars. Testing of the mortars for short stabilization periods (less than 24 hr) indicated the thermal records appear to be closely related to the initial times of setting. The initial time of setting of a mortar as determined by the pocket penetrometer and the thermal

data record seem to be less well correlated beyond 1 day for reasons that may not be related directly to the hydration of the cement. For very long stabilization, the initial time of setting by the penetrometer is faster than is indicated in the thermal record of the mortar or concrete. If used by the DELVO specialist for chart verification, the thermal record will serve as a monitor of the initial times of setting of the mortars collected for the verification. The record can be transferred directly into a laptop computer file. The data can then be converted to a usable format that shows the initial times of setting of the concrete mortars monitored. This would make the monitoring of the mixtures much more convenient to the DELVO specialist, who would otherwise spend a sleepless night monitoring the samples with a pocket penetrometer. The samples may be monitored either in the field or in a more convenient, secure area.

An example of the thermal record of a laboratory mortar is shown in Figure 28. The initial time of setting generally correlates well with the change in slope as the mortars emerge from the induction period and enter the acceleration phase of the hydration process.
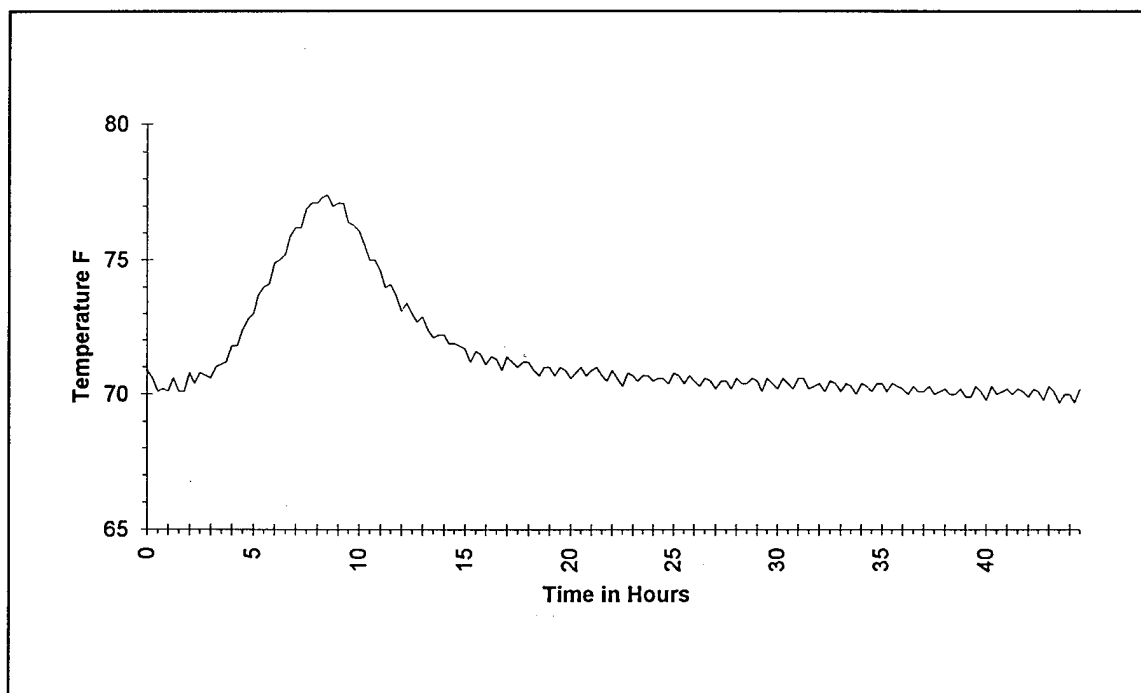
Figure 28. Example of thermal record of plain mortar

Infrared pyrometer

The hand-held, noncontact, infrared pyrometer was used to investigate the possibility of simplifying the determination of the temperature of returning loads of concrete. The pyrometer could be used by reading the temperature of the mixture through the mixer drum of the truck, from the discharge end of

the truck, or during discharge. The use of the device would help the producer using the instrument by reducing the necessity of discharging the concrete or could be used by a technician who must estimate the volume of the returning load. A pyrometer similar to the one used in this program can be directly connected to batching computers and used to compute the DELVO dosage rate from the verified DELVO dosage chart.

DELVO Chart Generator

The evolution of the DELVO Dosage Chart program began with the collection of DELVO database, which was assembled in anticipation of this project in the summer of 1990. The database was a list of the DELVO dosage charts that had been collected in the years prior to 1990. The cement brands used and an early attempt at rating the cements with respect to their reactivity were also included in the database. This reactivity was based on a statistical analysis after the charts had been collected. Critical information regarding the initial time of setting of the mixtures and initial times of setting of those DELVO-stabilized concrete mixtures was not recorded in the database, so simplification could not be based on this data set.

Statistical analysis of the first DELVO database produced the chart shown in Figure 29. This represents a contour plot for the same-day application of DELVO Stabilizer derived from that original database. It was determined that the resulting chart was too simplistic to account for the variations that would be induced by cements of differing reactivity. Therefore, the database did not have sufficient information to be used in simplification.

It was well understood that for the simplification to be possible, it would be necessary to isolate the behavior of individual cement paste, mortar, or concrete mixtures with and without DELVO Stabilizer. None of the information available for this purpose allowed for such a separation to be made. Several attempts were made to obtain field data and unused cement which would allow an isolation of the effect of DELVO Stabilizer either on mortar or concrete mixtures as influenced by individual cements. It was thought that individual cements could be characterized by laboratory testing that would differentiate between cements which required higher or lower dosages of DELVO Stabilizer.

Calorimetry of cements known to have significantly different DELVO Stabilizer dosage rate requirements was the first attempt at such a characterization. Calorimetry of the cements that exhibited shorter times of setting and consequently required higher dosages of DELVO Stabilizer were observed to be predominantly of a finer grind than those cements exhibiting longer initial times of setting. Fineness was thought to be a significant indicator of a feature of the cement which has been referred to as reactivity. Clinker phase composition of a cement, particularly the abundance of C_3A, was thought to be another factor which affected the reactivity of a particular
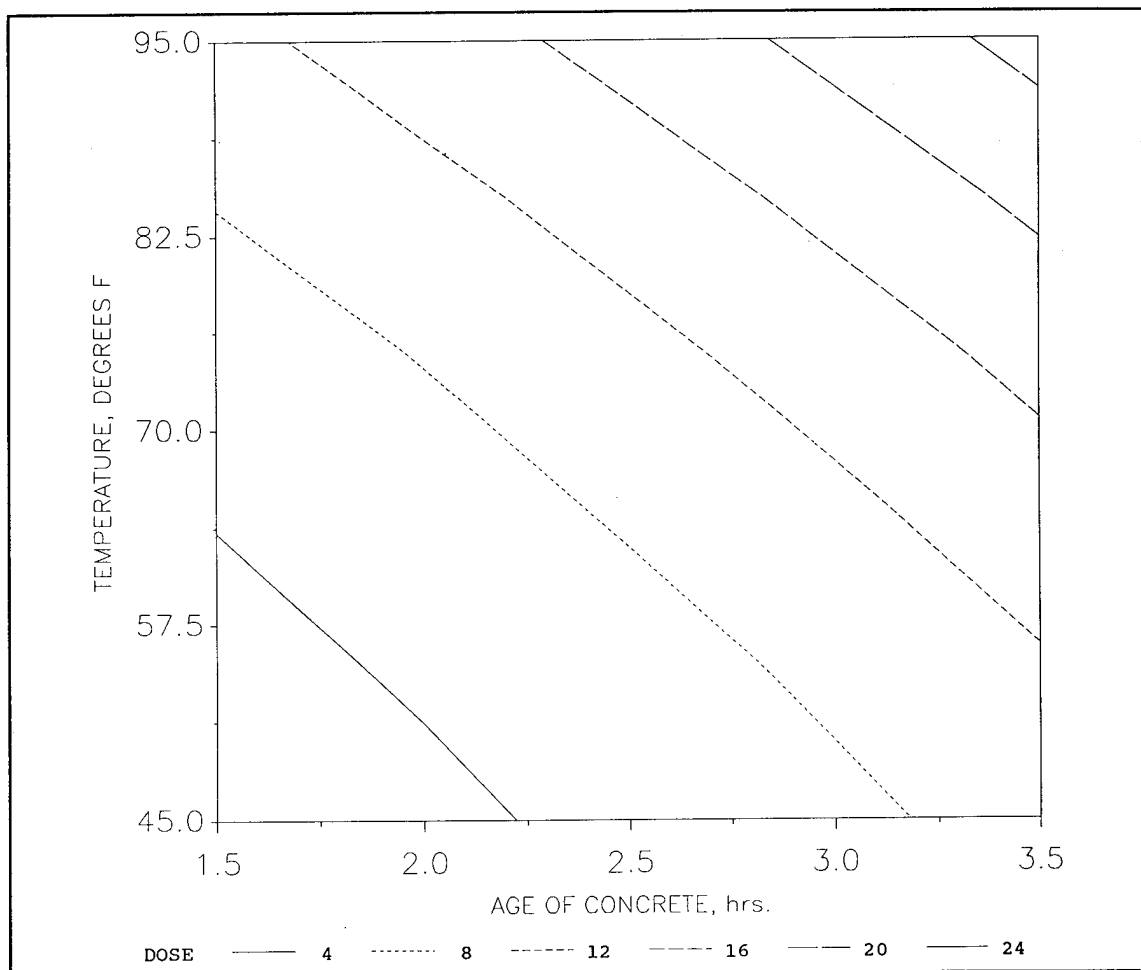
Figure 29. DELVO same-day stabilization dosages based upon original Florida database

cement. Reactivity was perceived as incorporating all the other factors of concrete (volume, temperature, age at stabilization, the presence of fly ash and of other admixtures in the mixture) that control the initial time of setting any concrete mixture. When calorimetry was stopped, fineness of a cement appeared to influence the initial time of setting of a mixture, but this was not statistically provable.

Mortar testing of cements was used to determine the possibility of predicting the initial time of setting of concrete at any temperature from a given time of setting at a known temperature. The cements were tested in a standardized mortar mixture at specific temperatures with and without DELVO Stabilizer. The influence of mortar age at the time of stabilization was also studied by monitoring the initial times of setting of mortars stabilized at the time of mixing, at 1 hr after mixing, and at 2 hr after mixing. The results of these mixtures are shown in Figures 30 and 31. From these tests it was supposed that the initial time of setting of any mortar mixture at any temperature within the range of the chart could be predicted if one initial time of setting of the mortar at a known temperature had been determined. From
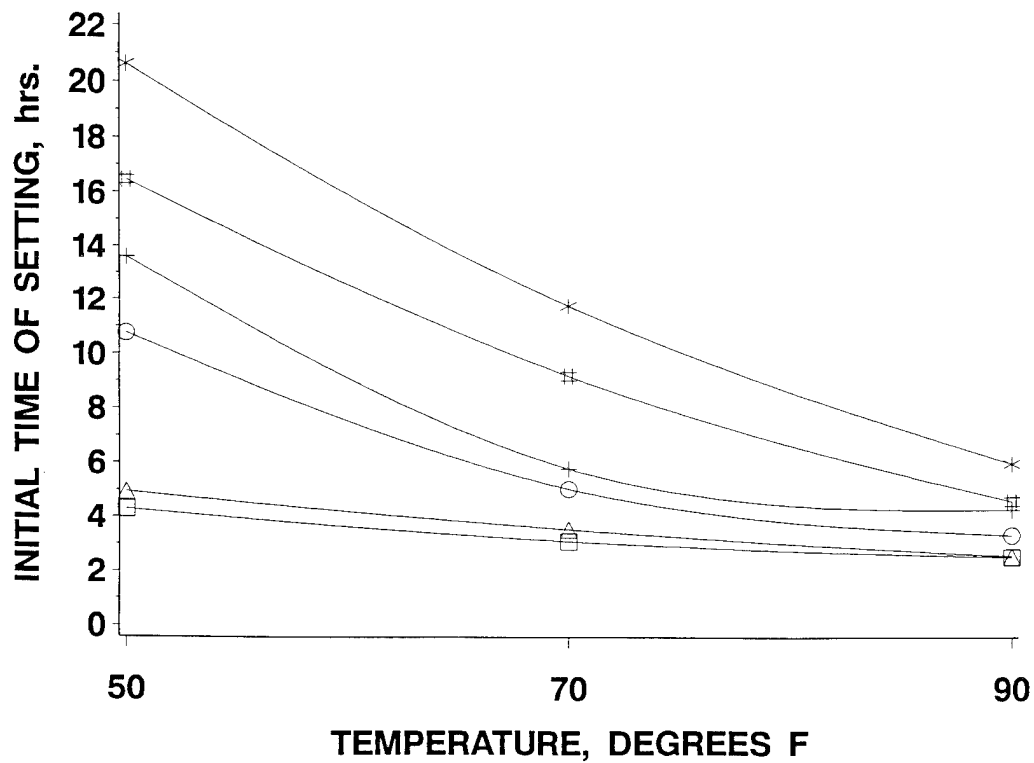
Figure 30. Influence of mortar age on time of setting using 10-oz DELVO Stabilizer/100 lb of cement
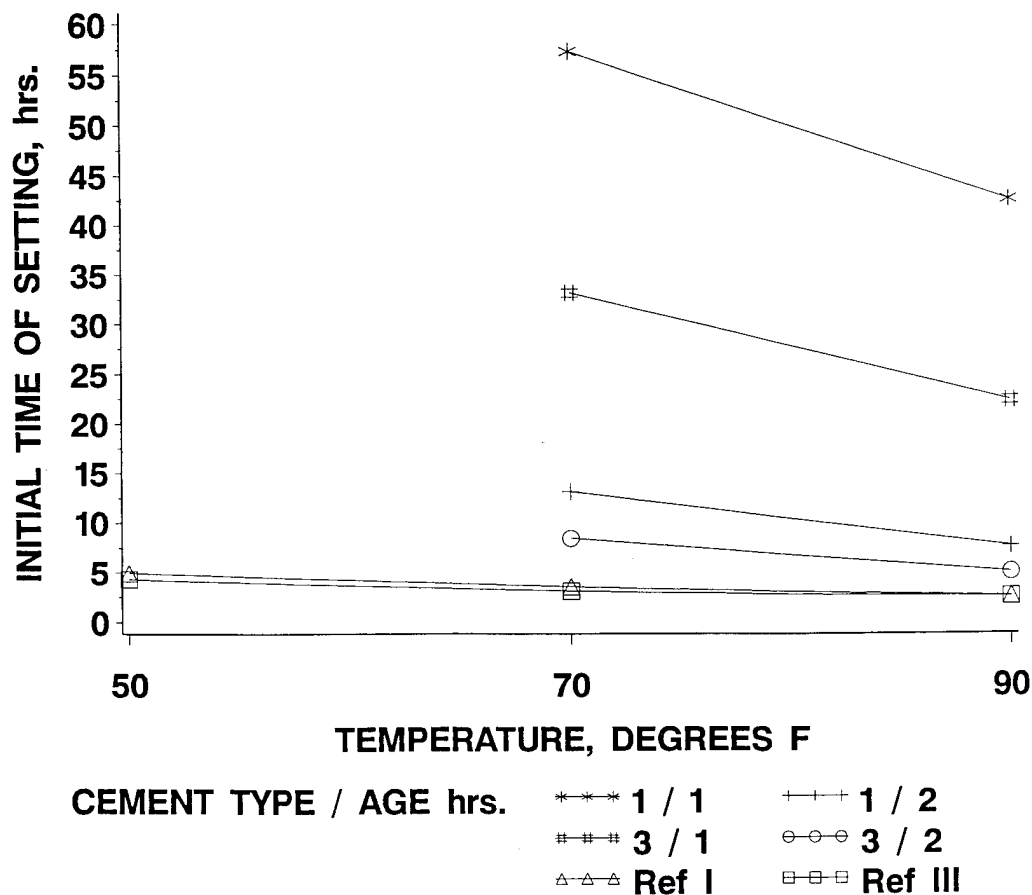
Figure 31. Influence of mortar age on time of setting using 20-oz DELVO Stabilizer/100 lb of cement

the observed initial time of setting, a theoretical time of setting could be predicted as a function of the ratio of the observed initial time of setting and temperature. From the theoretical initial time of setting, an age ratio could be calculated. The ratio is the age of the mixture at any time before initial time of setting and the theoretical initial time of setting of the mixture for each age and temperature condition in the DELVO dosage chart.

The initial time of setting of concrete mixtures in the field is typically determined with the use of screened mortars. It was thought that the laboratory-mixed mortars would resemble the screened concrete mortars in initial time of setting. All the untreated laboratory-mixed mortars exhibited initial times of setting that were much shorter than was expected for screened concrete mortars. The cause of these shorter than expected initial times setting was not determined, but it was believed that the results of the mortar testing would be a guide to the behavior of whole concrete as influenced by DELVO Stabilizer.

Figure 27 is the graphical representation of the Florida database plotted as the ratio of age divided by the theoretical time of setting versus the square root of the DELVO Stabilizer dosage rate. The two outer dotted lines represent the 95-percent prediction bands. The central line is the prediction of the square root of the DELVO Dosage rate as related to the ratio of the age of the mixture at stabilization divided by the theoretical time of setting. The DELVO Stabilizer dosage is then adjusted by the program for the presence of fly ash and an admixture. This yields the DELVO dosage rate for each cell of the same-day DELVO dosage chart. From the input data of the specific mixture, the program determines the ratio of the concrete age to the theoretical time of setting of the mixture. If the theoretical initial time of setting of the mixture minus the age of the mixture is greater than or equal to 1, the generator prints "*" in the cell, indicating that stabilization is not recommended. The overnight DELVO dosage chart entries are then derived from the same-day chart by a multiplier which varies from 3 to 4. This multiplier was based on the conversion of verified same-day charts to overnight chart data from the Florida database.

Use of the DELVO Chart Generator

When the DELVO Chart Generator is installed and running on a computer, all inputs to the program are prompted for the concrete temperature, the initial time of setting, the presence of fly ash and accelerators, and the cement factor. The concrete volume to be stabilized is also prompted so that the generator will print out a chart specifically for the number of cubic yards to be stabilized. From the input information, the theoretical initial time of setting of the mixture is calculated and displayed for the midpoint of each thermal category. The program then assigns a ratio of the age of the mixture with respect to the theoretical initial time of setting to all the combinations of age ratios and temperatures in the DELVO dosage chart, computing and displaying the DELVO Stabilizer for each condition. The resulting charts on the first page (Figure 32) are shown as the dosage rates as ounces per hundredweight of cement, or in ounces per cubic yards as calculated for the volume to be stabilized. The second page of the printout (Figure 33) displays the facility for the verification of the chart for the refined chart which the customer will use in production of concrete for the same-day application.

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Hit the CTRL and D characters simultaneously to start program.

Concrete Batching Temp	Initial Time of Setting, hrs.	Is Fly ash present?	Is an Accelerator present?	Cement Factor	Concrete Volume to be Stabilized, cu. yds.
70	5.0	n	n	450	1

Temp	55	65	75	85	95
Theoretical Time of Setting	7.5	5.7	4.4	3.6	3.1

COMPANY NAME
LOCATION

SAME DAY DOSAGE CHART, oz./cwt.

			Age (hrs)		
Temp	>1-1.5	>1.5-2	>2-2.5	>2.5-3	>3-3.5
90-99	8	14	*	*	*
80-89	6	10	15	*	*
70-79	3	7	11	16	20
60-69	1	4	7	11	15
50-59	1	2	4	7	10

SAME DAY DOSAGE CHART, oz./concrete vol., cubic yard(s)

			Age (hrs)		
Temp	>1-1.5	>1.5-2	>2-2.5	>2.5-3	>3-3.5
90-99	36	63	*	*	*
80-89	27	45	68	*	*
70-79	14	32	50	72	90
60-69	5	18	32	50	68
50-59	5	9	18	32	45

* Stabilization NOT recommended.

NOTES:

1) Take CONCRETE TEMPERATURE.

2) Add sufficient water to the returned concrete to get within 6-7 inch slump range prior to stabilization.

3) Add required amount of DELVO Stabilizer to the returned concrete and mix for 5-7 minutes.

4) Batch fresh concrete within 1/2 hour of stabilization, unless otherwise specified. For every 1 cu. yd. of stabilized concrete, a minimum of 1 cu. yd. of fresh concrete must be batched on top.

Figure 32. DELVO dosage chart generated by DELVO Chart Generator program for same-day stabilization

COMPANY NAME   0

LOCATION   0

SAME DAY DOSAGE CHART, oz./cwt. (after verification)

Temp	>1-1.5	>1.5-2	Age (hrs) >2-2.5	>2.5-3	>3-3.5
100-109	15	24	*	*	*
90-99	11	18	24	*	*
80-89	8	13	19	25	*
70-79	5	9	14	20	25
60-69	3	6	9	14	19
50-59	1	3	6	9	13

Press the ESCAPE key to return to the main menu.

SAME DAY DOSAGE CHART, oz./ vol., cubic yard(s) (after verification)

Temp	>1-1.5	>1.5-2	Age (hrs) >2-2.5	>2.5-3	>3-3.5
100-109	*	*	*	*	*
90-99	110	180	240	*	*
80-89	80	130	190	250	*
70-79	50	90	140	200	250
60-69	30	60	90	140	190
50-59	10	30	60	90	130

* Stabilization NOT recommended.
NOTES:

1) Take CONCRETE TEMPERATURE.

2) Add sufficient water to the returned concrete to get within 4-6 inch slump range prior to stabilization.

3) Add required amount of DELVO Stabilizer to the returned concrete and mix for 5-7 minutes.

4) Batch fresh concrete within 1/2 hour of stabilization, unless otherwise specified. For every 1 cu. yd. of stabilized concrete, a minimum of 1 cu. yd. of fresh concrete must be batched on top.

Figure 33. DELVO dosage chart generated by DELVO Chart Generator program after verification of dosages for same-day stabilization

COMPANY NAME   0

LOCATION   0

OVERNIGHT DOSAGE CHART, oz./cwt.

Temp	>1-1.5	>1.5-2	Age (hrs) >2-2.5	>2.5-3	>3-3.5
90-99	44	68	84	*	*
80-89	34	52	71	88	*
70-79	24	39	56	75	88
60-69	18	28	38	56	71
50-59	7	15	27	38	52

OVERNIGHT DOSAGE CHART, oz./ vol., cubic yard(s)

Temp	>1-1.5	>1.5-2	Age (hrs) >2-2.5	>2.5-3	>3-3.5
90-99	440	675	840	*	*
80-89	340	520	713	875	*
70-79	238	390	560	750	875
60-69	180	281	383	560	713
50-59	65	150	270	383	520

* Stabilization NOT recommended.

NOTES:

1) Take CONCRETE TEMPERATURE.

2) Add sufficient water to the returned concrete to get within 7-9 inch slump range prior to stabilization.

3) Add required amount of DELVO Stabilizer to the returned concrete and mix for 5-7 minutes.

4) For every 1 cu. yd. of stabilized concrete, a minimum of 2 cu. yd. of fresh concrete must be batched on top.

Figure 34. DELVO dosage chart generated by DELVO Chart Generator program for overnight stabilization

COMPANY NAME   0

LOCATION   0

OVERNIGHT DOSAGE CHART, oz./cwt. (after verification)

Temp	Age (hrs)				
	>1-1.5	>1.5-2	>2-2.5	>2.5-3	>3-3.5
90-99	44	68	84	*	*
80-89	34	52	71	88	*
70-79	24	39	56	75	88
60-69	18	28	38	56	71
50-59	7	15	27	38	52

Press the ESCAPE key to return to the main menu.

OVERNIGHT DOSAGE CHART, oz./ vol., cubic yard(s) (after verification)

Temp	Age (hrs)				
	>1-1.5	>1.5-2	>2-2.5	>2.5-3	>3-3.5
90-99	440	675	840	*	*
80-89	340	520	713	875	*
70-79	238	390	560	750	875
60-69	180	281	383	560	713
50-59	65	150	270	383	520

* Stabilization NOT recommended.

NOTES:

1) Take CONCRETE TEMPERATURE.

2) Add sufficient water to the returned concrete to get within 7-9 inch slump range prior to stabilization.

3) Add required amount of DELVO Stabilizer to the returned concrete and mix for 5-7 minutes.

4) For every 1 cu. yd. of stabilized concrete, a minimum of 2 cu. yd. of fresh concrete must be batched on top.

Figure 35. DELVO dosage chart generated by DELVO Chart Generator program after verification of dosages for overnight stabilization

As in the past, the customer receives a DELVO Stabilizer dosage chart and will perceive no operational differences. Because there should be no need for an initial evaluation, only the verification procedure should require the use of customer's trucks.

8   DELVO and the DELVOCRETE System

Background

In late 1989, prior to the DELVO-CPAR agreement, the original formulation of DELVO Stabilizer was changed. A transitional period took place in which the original formulation of DELVO Stabilizer was replaced by the newer formulation, referred here as the U.S. formulation during 1990. In the conventional uses of the product, long-haul, same-day, and overnight, the performance of U.S. DELVO Stabilizer is similar to that of the original formulation of DELVO Stabilizer. The U.S. formulation of DELVO Stabilizer was to be used throughout the United States for all applications.

In Europe, the formulation of DELVO Stabilizer was not changed and was incorporated into the application of DELVO technology for shotcrete practice; it was called the DELVOCRETE System. The use of DELVO Stabilizer in shotcrete practice was introduced in 1990 and is currently being used for rock stabilization in mines and tunnels and for other repair applications where shotcrete has been specified. The DELVOCRETE System resembles the long-haul application of DELVO Stabilizer with the exception that the stabilized shotcrete mixtures are activated at any time within the stabilization period by the use of proprietary admixtures that rapidly end the stabilization of the concrete, cause quick initial setting, and promote rapid early-strength development of the concrete after it is sprayed. The performance of such stabilized and activated shotcrete mixtures is similar to those of conventional shotcrete mixtures.

In conventional practice, the shotcrete mixtures are usually used within 1-1/2 to 2 hr after batching. This is referred to as the 90-min rule. Shotcrete applied within this time usually has plastic characteristics appropriate for use. The rule dictates that on a jobsite, shotcrete mixtures older than 90 min may be rejected because the pumpability, rebound, and bonding characteristics of the sprayed mixtures deteriorate after that time. Rejection of loads or clogging of equipment caused by shotcrete aged beyond the 90-min limit increases delays in the application of the shotcrete, requiring frequent equipment clean-out procedures that increase the waste of concrete and further

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complicate the placement of the concrete. For the shotcrete placed within the 90-min limit, consistency and rebound characteristics of the shotcrete mixtures deteriorate as they approach the end of their useful time limits, or potlife.

Use of the DELVOCRETE System can extend the potlife of the concrete mixtures hours beyond 90 min after batching, retain the consistency of the shotcrete mixtures throughout the stabilization period, reduce rebound of the sprayed shotcrete when applied, and reduce or eliminate waste or rejection of loads of shotcrete due to the age of the shotcrete mixtures. These features should significantly reduce cleanup activities of the site and reduce delays caused by cleaning of equipment used during and after application of the shotcrete.

In Europe, the DELVOCRETE System was restricted to the original DELVO Stabilizer formulation when it was determined that the acceleration or activation of mixtures stabilized with the U.S. DELVO Stabilizer was slow to respond to all shotcrete accelerator/activators. The DELVOCRETE System is now actively marketed and used in shotcreting practice in Europe for both the wet and dry shotcrete processes. Activities for this portion of the CPAR project were intended to confirm the performance of U.S. DELVO Stabilizer-treated shotcrete mixtures and to determine if the slowed response of those mixtures to activating admixtures could be circumvented. Interest was expressed in the use of DELVO Stabilizer in shotcrete for rock support in a nickel mine in Ontario, Canada, which also required laboratory testing in the absence of shotcrete pumping and spraying equipment.

Laboratory and Field Testing Activities

Testing for this portion of the CPAR project began with an evaluation of the activation of shotcrete mixtures treated with the original DELVO Stabilizer, referred to as the DELVOCRETE Stabilizer, and comparative studies of the laboratory performance of mixtures treated with the DELVOCRETE Stabilizer or U.S. DELVO Stabilizer, and activated with a conventional shotcrete accelerator.

A preliminary test of the feasibility of the use of U.S. DELVO in shotcreting activities was conducted at a warehouse facility. Two small panels were shot using a bagged shotcrete mixture stabilized with U.S. DELVO Stabilizer. The shotcrete mixture was subsequently activated with a maximum dosage of a conventional aluminate-based shotcrete accelerator/activator. This test confirmed that the plastic character of the mixtures would be retained beyond the 90-min rule with the use of U.S. DELVO Stabilizer. When activated, these stabilized mixtures exhibited what was regarded as slow activation and rate of hardening. Relative to standard shotcrete applications, the initial times of setting were relatively long with slow early-strength production that was not considered appropriate to the production of shotcrete for rock support. For this study, the objective was for activated shotcrete mixtures to produce initial times of setting (I_s) of under 3 min and a final time

of setting (F_s) in approximately 9 min. These initial and final times of setting were objectives to which the performance of the shotcrete mixtures were compared. Relatively slow strength development of activated shotcrete treated with U.S. DELVO formulation had been previously observed in the European application of the technology for shotcrete studies. Continued testing for this portion of the project was intended to study the phenomenon with the intent of finding an accelerator/activator that would promote a more rapid acceleration of DELVO Stabilized shotcrete mixtures, while continuing the testing of shotcrete mixtures stabilized with the original DELVO Stabilizer formulation, now referred to as DELVOCRETE Stabilizer.

Laboratory testing

Laboratory shotcrete mixtures fabricated with Types I and II cements were stabilized with a low dosage of DELVOCRETE Stabilizer, 6 oz/100 lb of cement. U.S. DELVO Stabilizer was not used in this test. The mixtures were activated with varying dosages of two aluminate-based accelerator/activators to determine the effectiveness of DELVO in extending the workability of shotcrete mixtures and to determine the effect of two accelerator/activators on the rate of hardening and on the ultimate strength of the shotcrete mixtures. After stabilization, the mixtures were activated with conventional shotcrete accelerators at ages of 30 min and 4 hr after stabilization. The compressive strength development of those mixtures was monitored for 28 days, as shown in Figures D1-D6. The initial time of setting (I_s) and final time of setting (F_s) of the mixtures were determined by the use of Gillmore needles according to ASTM C 1102 (ASTM 1992j).

Conventional shotcrete accelerator/activators were used to compare their reactivity with shotcrete mortars treated with a low dosage of DELVOCRETE-stabilizer and to compare the response of mixtures made with Types I and II cement. The results of this test indicate that a DELVOCRETE-stabilized mortar made with Type II cement was more responsive to the activating admixtures in initial time of setting and strength development than shotcrete mixtures made with Type I cement. The results of this test indicate that, when activated, the shotcrete mixtures fabricated with Type II cement were more responsive to both accelerators at early ages and at 4 hr of age. The initial times of setting of the mixtures typically were faster when the mixtures were activated at later ages (4 hr) than at earlier ages (30 min). This is consistent with behavior observed in previous testing and in the European experience and suggests that older stabilized mixtures require less admixture to be activated.

In March 1993, laboratory testing began on other accelerator/activator materials thought to be applicable to the activation of shotcrete mixtures stabilized with U.S. DELVO Stabilizer. Testing included the use of thixotropic agents to reduce sagging of the applied shotcrete to vertical surfaces caused by the slow activation of the mixtures in these tests. These tests were discontinued because the acceleration and early-strength development of

the shotcrete mixtures were not considered to be fast enough for the application of the method to rock support.

Laboratory testing of shotcrete accelerator/activators on DELVO-stabilized shotcrete mixtures continued in April 1993. This testing compared the performance of the shotcrete mixtures stabilized with U.S. DELVO Stabilizer and the original DELVO Stabilizer at the maximum recommended dosage rate for the DELVOCRETE System, 2 percent by weight of cement and with a standard mortar fabricated with Types I or II cement. These mixtures were aged 48 hr before being accelerated with varying dosages of the DELVOCRETE Activator S-71, a proprietary activating admixture. Initial time of setting (I_s) and final time of setting (F_s) were monitored with strength development of the mixtures monitored to 28 days by compressive strength testing of cube specimens. The results of this testing are shown in Figures D7-D12, Appendix D.

In general, the mixtures stabilized with DELVOCRETE-stabilizer were activated more quickly than those mixtures treated with U. S. DELVO Stabilizer, and as was previously observed, the mixtures fabricated with Type II cement were more quickly activated than those fabricated with Type I cement. One exception to this was observed in the test of the Type I shotcrete mixture activated with the highest maximum recommended activator dosage, 8 percent by mass of cement (Figure D9). The initial time of setting was equal to that of the initial time of setting of the DELVOCRETE Stabilized mixture, and the final time of setting of the U.S. DELVO Stabilized mixture was faster than that of the DELVOCRETE-stabilized mixture. It should be noted that this particular mixture was stiff when activated, and the cement hydration may have entered the acceleration phase by the time it was activated. At the time of activation, 48 hr, all the mixtures fabricated with Type II cements were plastic, in contrast to the stiffer mixtures fabricated with Type I cement. It is speculated that the early final time of setting, illustrated in Figure D11, was a result of increased acceleration of a mixture that was already naturally accelerated after the DELVO Stabilizer dosage had begun to wear off.

By August 1993, the proprietary DELVOCRETE Activator S-71 had been determined to be the most effective activator used with DELVOCRETE Stabilizer, and all following testing was restricted to this activating admixture. In anticipation of field testing planned for late August 1993 at a nickel mine in Ontario, Canada, laboratory testing of shotcrete mixtures stabilized with DELVOCRETE Stabilizer was performed with one high-range water-reducing admixture (HRWR). This was done to determine if there would be an adverse response of the stabilized mixtures to the activation by the addition of other admixtures. U.S. DELVO Stabilizer was not tested because DELVOCRETE Stabilizer was the only stabilizer available at the field test site. Requirements for the performance of the shotcrete were that the initial time of setting be 3 min or less with a 28-day compressive strength of 4,500 psi with a w/c of 0.4. On delivery to the mine, the slump of the mixtures was to be 8 in. with 3- to 4-in. slump when aged and pumped. In the laboratory, the mixtures

were made with cement reported to be in use at the jobsite, and the mixture proportions conformed to that being used at the site with the exception that the sand and pea gravel were laboratory stock from the Master Builders' laboratory. The slump was monitored by a nonstandard mini-slump test, and flow of the mixtures was monitored by flow table. Flow of the mixtures, treated with DELVOCRETE Stabilizer was monitored with time to determine the length of time the mixtures would be affected by the presence of the HRWR admixture.

For mixtures stabilized with 1.5-percent DELVOCRETE Stabilizer, a midrange dosage for stabilization, monitoring of the flow, and slump of the stabilized mixtures indicated that the use of the HRWR admixture would produce a temporary improvement of the flow with respect to the mixtures which did not contain the admixture. Within about 3 hr, there was essentially no difference in the flows of the treated and untreated, stabilized mixtures, and by 24 hr, the mixtures had stiffened to 8-percent flow without the admixture and 10-percent flow with the HRWR admixture. When these mixtures were activated with the maximum recommended dosage rate of Activator S-71, (8 percent by mass of cement) at ages of 1 and 24 hr after stabilization, the later activation showed an initial time of setting of 3 min and 10 sec. Comparisons of the activation of these mixtures at 1 and 24 hr after batching showed that the presence of HRWR slowed the activation slightly when activated at the maximum S-71 dosage. The w/c of the mixtures that met the requirements of the plastic shotcrete were 0.5 to 0.52, but the strengths of the activated mixtures exceeded 5,000 psi by 7 days after activation. This information was made available to personnel testing the shotcrete mixtures batched at the nickel mine for field testing in the latter part of August 1993. Subsequent field testing used another mixture proportion and a water-reducing admixture other than that used in the laboratory testing.

To show the performance of the placed shotcrete mixtures with respect to strength development and shrinkage of the mixtures when stabilized within the recommended dosage range of DELVOCRETE Stabilizer and activated with only Activator S-71, one final laboratory test was conducted in March 1994. The compressive strength of the hardened shotcrete and the shrinkage of the hardened specimens were monitored for 28 days after activation. Length-change bars and 2-in. compressive-strength cubes were monitored at ages of 1, 4, and 6 hr and at 1, 7, and 28 days after activation. The DELVOCRETE Stabilizer dosage rates were varied from the minimum recommended level of 0.6 percent by mass of cement to the maximum recommended dosage of 2 percent by mass of cement in the mixture with one intermediate dosage of 1 percent tested, the more commonly used dosage rate. Depending on the dosage rate and the length of the stabilization, the mixtures were activated at ages of 1, 6, 9 and 24 hr. The mixtures dosed with the lowest stabilizer dosage, lasting only about 10 hr, were not activated at 24 hr. For this test, only Type I cement was used. For activation, the maximum recommended dosage rate of 8 percent of S-71 was used at 1 hr of age of stabilization. Subsequent activations were at the more moderate level of 6-percent S-71 by mass of cement.

Figures D13 to D20 show the compressive-strength development, shrinkage, and initial times of setting and final times of setting of treated and untreated shotcrete mixtures for this test. The maximum dosage of the activating admixture was 8 percent by mass of cement, and the unactivated shotcrete mixture is compared to the activated reference mixture. Shrinkage was observed to be greater in the activated mixtures than in the reference mixture, as influenced by the use of the activating admixture. That higher dosages of any accelerating admixture increase shrinkage is a well-known phenomenon in the shotcrete practice. That trend is observed in the relative compressive-strength development of the reference, unactivated mixture and the reference mixture activated at the maximum dosage rate of the accelerator/activator. Compared to the reference mixture, the ultimate compressive strength of the activated mixture was conspicuously lower than the reference mixture. Shrinkage of the reference shotcrete mixture, accelerated with the activating admixture, exhibited significant shrinkage compared to that of the reference mixture.

When the concrete mixtures were treated with DELVOCRETE Stabilizer, the first activation at 1 hr of age was at the maximum of 8-percent activator to reduce the initial time of setting of the mixtures. Subsequent activations were at 6 percent because the initial times of setting were expected to be shorter, requiring less of the activating admixture. The mixtures activated with lower activator dosage rate, 6 percent by mass of cement, also showed less shrinkage than the mixtures activated at 8 percent. The least shrinkage and the best compressive strength development for all dosage levels of DELVOCRETE Stabilizer rates were for those mixtures activated after 9 hr of stabilization.

Field testing

Complete testing of the DELVOCRETE System has not yet occurred, but interest has been expressed in the use of the DELVOCRETE System in shotcrete by methodically building an experience base and testing of the stabilization of concrete and shotcrete mixtures. This activity will ultimately result in the use of the DELVOCRETE System for rock support in a nickel mine at Sudbury, Ontario, Canada.

A seminar was held in November 1992 with 60 management and engineering personnel of the mine attending. In January and February 1993, the first phase of field studies in the use of DELVOCRETE Stabilizer in shotcrete activities began at the mine. The preliminary results of DELVO stabilization of mortars after batching for both the wet- and dry-shotcrete processes were considered successful. No activation of the mixtures was performed, and none of the concrete was sent to working elevations within the mine. The mining company expressed continued interest in studying the use of DELVO in shotcrete, and the second phase of study was planned in which the mixtures would be accelerated after stabilization.

The next phase was to prove that the mixtures would be stabilized long enough and be of a consistency necessary to be delivered to working levels of the mine without clogging the drop pipes. From the laboratory testing of early August, it was determined that a stabilized shotcrete mixture containing a high-range water reducer could be produced, possessing the necessary flow and slump characteristics to be dropped through the pipes to the working levels of the mine. The testing took place aboveground 23-25 August 1993. The length of stabilization of the mixtures was related to DELVO Stabilizer dosage rates for the concrete materials intended to be used in the mine, and activation of the mixtures was also demonstrated on vertical surfaces at slumps as high as 8 in. with no sagging of the applied shotcrete. Later in the week, stabilized shotcrete mixtures were dropped through the drop pipe to demonstrate the ability of these mixtures to be transported to working levels in the mine.

In March 1994, the decision was made that the DELVOCRETE formulation would be the only formulation to be used in the DELVOCRETE System for shotcrete. Based on the testing to date, the stabilization times of 8 to 12 hr may be most appropriate for rock support in tunneling, a time range which would cover a full work shift. The DELVOCRETE Stabilizer dose rates that provided the most appropriate length of stabilization with appropriate activation times were found to be 0.6 to 1.0 percent by mass of cement. For most rock support activities, this dosage range exhibited appropriate initial times of setting and early-strength development after the concrete mixtures were activated. Based on the testing, initial times of setting, and early strength, production of the activated concrete mixtures would be suitable for rock support activities.

By the end of the DELVO CPAR project, the use of DELVOCRETE Stabilizer with a proprietary activator was approved for production and use in the United States and Canada within Master Builders production facilities. Thorough testing of the concept in Canada, at the nickel mine in Ontario, Canada, was completed in May 1994, and application of DELVO-stabilized shotcrete was expected to begin in the mine pending the completion of a drop pipe and liner specifically intended for the delivery of DELVOCRETE-stabilized concrete mixtures to the working levels in the mine. Shotcrete mixtures will be treated with DELVOCRETE Stabilizer to stabilize the mixtures for periods of 8 to 12 hr. In this way, shotcrete batched at the beginning of a shift will be delivered to the working levels of the mine where the shotcrete can be applied at any time during the shift without concern for age or consistency changes of the mixture. Since age limits of the shotcrete will be eliminated during the stabilization time and the consistency of the mixtures will remain constant during the stabilization time, waste of concrete during application should be reduced or eliminated.

In another application, concrete mixtures treated with U.S. DELVO Stabilizer will be delivered to shallow levels of the mine by ramp access from the surface. In this application, the concrete will be treated by the addition of U.S. DELVO Stabilizer with the mixing water in a procedure that resembles

the long-haul application. This concrete will not be sprayed but will be used for other purposes within the mine. When needed, the stabilized concrete will be activated with small dosages of a standard, nonchloride shotcrete accelerator/activator to slowly activate as the admixture effect wears off. In other cases, the stabilized mixtures may not be activated but will be placed and will harden as the effects of the DELVOCRETE Stabilizer wears off, producing concrete that should meet the ultimate compressive strength after about 28 days. Ideally, all the concrete batched will be used, eliminating the need for the disposal of waste concrete that would be a disposal problem underground and would have to be hauled to the surface.

9 Conclusions and Recommendations

Conclusions

Standard DELVO applications

The results of the investigation conducted at WES on the use of DELVO Stabilizer for same-day, overnight, and long-haul applications indicated the following:

a. The fresh properties of all mixtures representing the three stabilization applications were comparable to those of the untreated reference mixtures.

b. Fresh concrete at laboratory temperatures stabilized for same-day, overnight, or long-haul applications in accordance with the procedures recommended by Master Builders had both compressive and flexural strengths 90 percent or greater than those of untreated reference mixtures. At several of the ages that specimens were tested, the stabilized concretes were greater than 100 percent of the unstabilized reference mixtures.

c. The resistance of the stabilized mixtures to rapid cycles of freezing and thawing, as defined by the durability factor, approached 100 percent that of the reference mixtures, with the exception of two of the overnight stabilized mixtures. The mixtures had a durability factor relative to those of the respective reference mixtures of approximately 80.

d. The same-day and long-haul stabilized mixtures experienced drying shrinkage within 0.010 percent of that of the reference mixtures. The overnight stabilized mixtures generally sustained shrinkage equal to or slightly greater than 0.010 percent of that of the reference mixtures.

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e. The results of the chloride-ion penetration tests were somewhat variable but indicated that the stabilized and reference mixtures were of comparable quality with respect to chloride-ion penetrability.

f. Proper air-void systems for protecting the concrete from frost damage were achieved in both the stabilized and reference mixtures. Spacing factors were less than 0.008 in. for all mixtures.

g. The compressive and flexural strengths of same-day stabilized mixtures produced at approximately 95 °F were generally comparable to those of the reference mixtures; however, it did appear that the properties of one of the cements had a more pronounced effect on the compressive strengths of one of the stabilized mixtures.

h. The frost resistance of the same-day stabilized mixtures produced at elevated temperature was greater than that of the reference mixtures.

i. The drying shrinkage of the same-day stabilized mixtures produced at elevated temperature was approximately 0.010 percent greater than that of the respective reference mixtures.

j. The chloride-ion penetrability of the stabilized mixtures produced at elevated temperature was comparable to that of the reference mixtures.

Use of DELVO in lean mass concrete

The results of using DELVO Stabilizer in lean mass concrete typical of that used by the Corps of Engineers in civil works structures indicated that although the adiabatic temperature rise of the concrete containing the DELVO Stabilizer started slightly later, it was comparable to that of the unstabilized reference mixture after 3-days age. At approximately 28-days age, the two mixtures experienced approximately the same total adiabatic temperature rise.

The results of mechanical properties tests indicated that the DELVO-stabilized concrete had slightly higher compressive-strength and modulus-of-elasticity values at all ages tested and slightly lower specific creep. This combination of properties might result in higher thermally induced stresses in the stabilized concrete than in the unstabilized concrete. However, because of the lower w/c, the ultimate tensile-strain capacity of the stabilized mixture was slightly greater than that of the reference mixture, which might enable the stabilized concrete to sustain greater tensile strains.

Use of DELVO in mass RCC

With the use of DELVO Stabilizer, RCC can be retarded for prolonged periods of time. DELVO Stabilizer also has a water-reducing effect on RCC. Results of direct shear tests on jointed specimens molded in the laboratory

were mixed but seemed to indicate that shear strength could generally be improved if the lower layer could be maintained fresh.

Direct shear test results of jointed cores taken from the WES RCC test section showed an improvement in joint shear strength when the lower lift was maintained fresh using the DELVO Stabilizer rather than allowing it to harden and then applying a bedding mortar. The cohesion of the stabilized joint was approximately 60 percent of that of the parent concrete, while the cohesion of the mortared joint was only approximately 20 percent of the parent concrete. The number of tests for each condition was limited, but the data seem to indicate that stabilization of the lower lift with DELVO Stabilizer will significantly improve the shear strength of RCC lift joints.

Dosage simplification activities

Simplification procedures for determining DELVO Stabilizer dosages were developed for the same-day and overnight stabilization applications. The key to simplification is a proprietary computer program, the DELVO Chart Generator, developed by Master Builders, which generates DELVO dosage charts on the basis of prompted inputs of information which should be available to the DELVO specialist before visiting a new customer's facility. The program simplifies the development of the DELVO Stabilizer dosage chart by the DELVO technologist and reduces the time a customer's equipment must be used for trial mixtures.

A battery-powered, portable thermal data logger was found by Master Builders to be an effective method of monitoring initial times of setting of mortars in their laboratory testing. Testing of mortars for short stabilization periods (less than 24 hr) indicated the thermal records were closely related to the initial times of setting and were comparable to those determined using a pocket penetrometer. The use of thermal records will enable the DELVO technologist to monitor the initial times of setting of mortar samples collected for dosage chart verification. The records can be transferred to a computer data file and converted to a usable format that shows the initial times of setting of the concrete mortars monitored. This will eliminate the need for the DELVO technologist to manually monitor times of setting throughout the night and early morning hours after concrete is produced.

A hand-held, noncontact infrared pyrometer was evaluated by Master Builders for use in determining the temperature of returning loads of fresh concrete. The pyrometer may be used for determining the mixture temperature through the mixer drum of the truck, from the discharge end of the mixer drum, or from the actual discharged concrete. This device would assist the producer by reducing the necessity for discharging the concrete and could be done by the same technician who must determine the volume of the returned load. The device could also conceivably be interfaced to the concrete batching computer and used to compute the DELVO Stabilizer dosage rate from the verified DELVO dosage chart.

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Information developed from the simplification activities will aid in reducing the perception that DELVO Stabilizer is difficult to use. Because the dosage charts can be generated in the field, customers will see nearly immediate results. There should be no further need for testing of cements if accurate initial time of setting and temperature information is available and if the charts are verified prior to routine use. DELVO technology should be more attractive because the time necessary to generate and verify dosage charts will be reduced, along with the need to involve the producer's batching and mixing equipment.

Use of DELVO in shotcrete

Laboratory testing conducted by Master Builders indicated that the original formulation of DELVO Stabilizer can effectively extend the working time of shotcrete as needed and a proprietary activator may be used to rapidly end stabilization and promote strength development. This formulation, termed DELVOCRETE Stabilizer, is still currently available in Europe and has now been approved by Master Builders for production in the United States.

The information developed under this CPAR project has been used to support the DELVOCRETE System in the United States and Canada. Potential benefits of the DELVOCRETE System include:

a. Elimination or relaxation of the 90-min rule.

b. Extended useful lifetime of the plastic shotcrete mixture.

c. Reduction of rebound when the shotcrete is applied.

d. Consistent fresh characteristics during the potlife of the mixture.

e. Elimination of the need for onsite batching plants for shotcrete applications.

f. Reduction of waste and cleanup.

g. Reduced frequency or elimination of clean-out of pumps when delays occur during the shotcrete activity during the day or between shifts.

Recommendations

The objectives of this CPAR project were to verify the performance test results reported by Master Builders for some of the current standard applications of DELVO technology and to develop new applications for the technology which might reduce concrete mixture costs, increase concrete productivity, improve infrastructure durability, and reduce the adverse environmental impact associated with the disposal of waste concrete. The use

of DELVO Stabilizer in the same-day, overnight, and long-haul applications is a viable means of reducing the disposal of waste concrete. Additional research is recommended to confirm the length-change results reported herein for these applications. If drying shrinkage is notably increased when DELVO Stabilizer is used for overnight stabilization, then changes in the procedures followed for this application, or in the product formulation itself, may be warranted. Additional research is also recommended to evaluate the use of DELVO on concretes containing additional materials such as ground slag, pozzolans, and chemical admixtures, since DELVO is routinely used to stabilize mixtures containing these materials.

DELVO technology appears to have value in several new applications including RCC and shotcrete. The possible reduction or elimination of RCC lift-joint bedding mortar should reduce RCC construction costs even further. However, additional testing of cores from RCC placements made using field production, placing, and consolidation procedures and equipment is desirable to verify the joint shear strength results reported for this project. Independent laboratory and field research is also suggested to confirm the Master Builders test results on the use of DELVOCRETE for stabilizing shotcrete mixtures. Stabilized shotcrete may be particularly beneficial for use in repair of structures where the size of equipment staging areas is limited or where sites are remote. Although the results of this project indicate that DELVO Stabilizer is probably not an effective option for use in mass concrete, other applications which were not thoroughly investigated under this CPAR project do have significant potential. One of these is the use of DELVO to minimize construction joints in concrete paving. A significant effort has been made by Master Builders in researching this application, and plans were made in the Scope of Work for this CPAR project to evaluate this application. However, the field testing demonstrations required to perform this task could not be arranged within the time frame of the project. A brief summary of work conducted by Master Builders leading up to the CPAR project is provided in Appendix E.

References

American Society for Testing and Materials. (1991). *1991 Annual Book of ASTM Standards*. Philadelphia, PA.

a. ASTM C 138, "Standard test method for unit weight, yield, and air content (gravimetric) of concrete."

b. ASTM C 143, "Standard test method for slump of hydraulic cement concrete."

c. ASTM C 157, "Standard test method for length change of hardened hydraulic-cement mortar and concrete."

d. ASTM C 192, "Standard practice for making and curing concrete test specimens in the laboratory."

e. ASTM C 231, "Standard test method for air content of freshly mixed concrete by the pressure method."

f. ASTM C 260, "Standard specification for air-entraining admixtures for concrete."

g. ASTM C 403, "Standard test method for time of setting of concrete mixtures by penetration resistance."

h. ASTM C 457, "Standard test method for microscopical determination of parameters of the air-void system in hardened concrete."

i. ASTM C 494, "Standard specification for chemical admixtures for concrete."

j. ASTM C 666, "Standard test method for resistance of concrete to freezing and thawing."

k. ASTM C 1064, "Standard test method for temperature of freshly mixed portland-cement concrete."

l. ADTM C 1176, "Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table."

American Society for Testing and Materials. (1992). *1992 Annual Book of ASTM Standards*. Philadelphia, PA.

a. ASTM C 39, "Standard test method for compressive strength of cylindrical concrete specimens."

b. ASTM C 78, "Standard test method for flexural strength of concrete (using simple beam with third-point loading)."

c. ASTM C 150, "Standard specification for portland cement."

d. ASTM C 204, "Standard test method for fineness of portland cement by air permeability apparatus."

e. ASTM C 359, "Standard test method for stiffening of portland cement (mortar method)."

f. ASTM C 430, "Standard test method for fineness of hydraulic cement by the 45-μm (No. 325) sieve."

g. ASTM C 469, "Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression."

h. ASTM C 512, "Standard test method for creep of concrete in compression."

i. ASTM C 618, "Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland-cement concrete."

j. ASTM C 1102, "Standard test method for time of setting of portland-cement pastes containing accelerating admixtures of shotcrete by use of Gillmore needles."

k. ASTM C 1202, "Standard test method for electrical indication of concrete's ability to resist chloride-ion penetration."

American Society for Testing and Materials. (1993). *1993 Annual Book of ASTM Standards*. Philadelphia, PA.

a. ASTM C 94, "Standard specification for ready-mixed concrete."

b. ASTM C 494, "Standard specification for chemical admixtures for concrete."

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Appendix A
Individual Test Results for Temperature, Slump, Unit Weight, and Air Content

Table A1
Fresh Concrete Test Results (Laboratory-Temperature Concrete)

Mixture	Batch No.	Concrete Temp., °F	Slump, in.	Unit Wt, lb/ft³	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELREF-1	1	78	4	145.6	5.5	3:18	4:59
DELREF-1	2	76	3	144.8	6.2	4:00	5:48
DELREF-1	3	76	3-1/2	145.2	5.9	3:56	5:19
DELREF-2	1	75	3-1/2	144.0	6.0	5:05	6:50
DELREF-2	2	76	3	144.0	5.8	4:44	6:35
DELREF-2	3	77	3-1/2	144.8	5.5	4:31	6:19
DELREF-3	1	76	4	144.0	6.1	4:20	5:33
DELREF-3	2	77	3	146.8	5.5	4:06	5:29
DELREF-3	3	75	3-1/2	145.2	6.0	4:10	5:48
DELREF-4	1	76	3	144.0	5.7	4:09	6:08
DELREF-4	2	77	4	141.6	6.0	4:15	5:37
DELREF-4	3	77	4	140.8	6.5	3:50	5:22
DELSDY-1	1	75	3-3/4	144.6	6.3	4:33	5:45
DELSDY-1	2	76	3-3/4	145.2	6.3	4:25	5:33
DELSDY-1	3	76	3	--[1]	6.0	4:20	5:30
DELSDY-2	1	75	3-3/4	143.6	5.9	5:07	6:49
DELSDY-2	2	72	4	143.2	6.0	--	--
DELSDY-2	3	75	4	144.0	5.7	5:40	7:55
DELSDY-3	1	77	3-1/4	145.6	5.8	--	6:40
DELSDY-3	2	74	3	145.2	5.9	4:30	5:00
DELSDY-3	3	75	3-3/4	144.8	6.2	4:00	6:12
DELSDY-4	1	78	3-1/2	144.4	5.8	4:25	6:12
DELSDY-4	2	77	2-1/2	143.6	6.0	3:57	5:15
DELSDY-4	3	74	3-3/4	144.0	5.5	4:39	6:37

(Sheet 1 of 4)

[1] -- indicates test not conducted on this batch.

Table A1 (Continued)

Mixture	Batch No.	Concrete Temp., °F	Slump, in.	Unit Wt, lb/ft^3	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELOVN-1	1A	76	3-3/4	144.4	7.0	--	--
DELOVN-1	1B	76	3	143.6	7.4	3:18	4:43
DELOVN-1	2A	75	4	143.6	8.0	--	--
DELOVN-1	2B	74	4	146.0	5.9	4:09	5:27
DELOVN-1	3A	75	4	142.4	8.2	--	--
DELOVN-1	3B	77	3-1/2	146.0	6.0	4:20	5:59
DELOVN-2	1A	71	4-1/2	144.8	6.2	--	--
DELOVN-2	1B	71	3-1/4	146.4*	5.3	4:40	6:25
DELOVN-2	2A	75	3-3/4	143.6	6.3	--	--
DELOVN-2	2B	77	3-1/4	142.4	7.2	4:15	5:58
DELOVN-2	3A	75	4	144.0	6.4	--	--
DELOVN-2	3B	74	3-1/4	143.6	7.0	4:22	5:53
DELOVN-3	1A	77	3-1/2	145.6	6.4	--	--
DELOVN-3	1B	76	3-1/2	147.2	5.6	4:22	5:43
DELOVN-3	2A	75	3-1/2	144.0	7.0	--	--
DELOVN-3	2B	77	4-3/4	146.0	5.7	4:38	--
DELOVN-3	3A	76	3-3/4	146.0	5.8	--	--
DELOVN-3	3B	75	5-1/4	146.4	5.9	5:25	6:48
DELOVN-4	1A	72	3-1/2	143.6	6.8	--	--
DELOVN-4	1B	77	3-3/4	145.6	5.7	4:52	6:29
DELOVN-4	2A	77	3-1/2	142.0	7.4	--	--
DELOVN-4	2B	76	3-1/4	144.8	5.5	5:14	6:10
DELOVN-4	3A	76	3-1/4	143.6	6.8	--	--
DELOVN-4	3B	75	3-1/2	145.6	5.4	4:26	5:54

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Table A1 (Continued)

Mixture	Batch No.	Concrete Temp., °F	Slump, in.	Unit Wt, lb/ft³	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELLHL-1	1A	69	3-1/4	--	--	--	--
DELLHL-1	1B	69	4-1/4	143.6	7.0	--	--
DELLHL-1	1C	70	2-1/2	146.4	5.5	7:55	9:46
DELLHL-1	2A	71	2-1/4	--	--	--	--
DELLHL-1	2B	72	3-3/4	144.8	6.6	--	--
DELLHL-1	2C	70	2	145.6	6.0	7:40	9:47
DELLHL-1	3A	69	2-3/4	--	--	--	--
DELLHL-1	3B	71	3-3/4	144.8	6.2	--	--
DELLHL-1	3C	65	2-1/2	145.6	5.9	8:07	9:36
DELLHL-2	1A	65	3-1/4	--	--	--	--
DELLHL-2	1B	64	4-3/4	143.6	6.2	--	--
DELLHL-2	1C	62	3	142.8	6.3	9:12	10:58
DELLHL-2	2A	66	3-1/2	--	--	--	--
DELLHL-2	2B	63	4-3/4	143.6	6.3	--	--
DELLHL-2	2C	63	3	144.0	5.9	8:17	10:35
DELLHL-2	3A	67	2-1/2	--	--	--	--
DELLHL-2	3B	64	4-1/4	142.4	6.7	--	--
DELLHL-2	3C	63	2-1/2	144.8	6.0	8:51	10:35
DELLHL-3	1A	67	3-1/4	148.0	4.2	--	--
DELLHL-3	1B	67	5-1/4	143.6	6.8	--	--
DELLHL-3	1C	66	3-1/2	144.0	6.8	8:42	10:07
DELLHL-3	2A	68	3	147.2	4.3	--	--
DELLHL-3	2B	68	5	144.0	6.2	--	--
DELLHL-3	2C	68	3-1/2	144.0	6.0	8:24	9:34
DELLHL-3	3A	64	3-1/2	146.8	5.0	--	--
DELLHL-3	3B	64	5	144.4	6.5	--	--
DELLHL-3	3C	63	3-1/2	144.8	6.0	6:45	7:48

(Sheet 3 of 4)

Appendix A   Individual Test Results for Temperature, Slump, Unit Weight, and Air Content

Table A1 (Concluded)

Mixture	Batch No.	Concrete Temp., °F	Slump, in.	Unit Wt, lb/ft³	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELLHL-4	1A	63	3-3/4	144.8	5.0	--	--
DELLHL-4	1B	63	5	142.8	6.5	--	--
DELLHL-4	1C	67	3	143.2	6.0	10:37	12:02
DELLHL-4	2A	69	4-1/4	145.6	4.5	--	--
DELLHL-4	2B	70	5-1/2	143.2	5.8	--	--
DELLHL-4	2C	69	3-1/4	144.0	5.6	9:08	10:30
DELLHL-4	3A	68	3-1/4	145.6	4.6	--	--
DELLHL-4	3B	68	4-1/4	142.8	6.0	--	--
DELLHL-4	3C	68	2-3/4	144.8	5.4	8:27	9:55

(Sheet 4 of 4)

Appendix A   Individual Test Results for Temperature, Slump, Unit Weight, and Air Content

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Table A2
Fresh Concrete Test Results (Elevated-Temperature Concrete)

Mixture	Batch No.	Concrete Temp., °F	Slump, in.	Unit Wt, lb/cu ft	Air Content, percent	Initial Time of Setting, hr:min	Final Time of Setting, hr:min
DELREFH-1	1	95	4	142.8	7.1	4:00	5:29
DELREFH-1	2	95	3	144.8	6.3	4:00	5:18
DELREFH-1	3	93	4	144.4	6.1	4:05	5:36
DELREF-2	1	98	3-3/4	144.0	5.9	5:10	7:15
DELREF-2	2	95	3-1/2	144.4	5.4	4:35	6:20
DELREF-2	3	98	3-1/2	143.2	6.5	4:35	6:36
DELSDY-1	1	93	3	146.8	5.5	4:03	5:28
DELSDY-1	2	93	3-1/4	145.2	6.0	4:13	5:17
DELSDY-1	3	96	3	145.2	5.9	3:37	4:50
DELSDY-2	1	96	3-1/2	144.4	6.0	4:50	6:10
DELSDY-2	2	96	3-1/2	142.0	6.3	4:47	5:57
DELSDY-2	3	96	3-1/2	143.2	6.2	4:40	6:40

Appendix B
Individual Compressive-Strength Test Results and Modulus-of-Elasticity Values

Table B1
Compressive-Strength and Modulus-of-Elasticity Test Results
(Laboratory-Temperature Concrete)

Mixture	Batch No.	Compressive Strength, psi					28-day Modulus of Elasticity, 10^6 psi
		1-day	3-day	7-day	28-day	6-month	
DELREF-1	1	1950	2480	3520	4560	--[1]	5.39
DELREF-1	2	1660	2560	3100	3890	4810	5.06
DELREF-1	3	1540	2520	3130	4210	5110	5.10
DELREF-2	1	1700	2780	3560	4160	4880	5.57
DELREF-2	2	1910	2980	3430	4230	4950	4.76
DELREF-2	3	1900	2950	3610	4350	5060	5.09
DELREF-3	1	2090	2960	3640	3820	5590	5.26
DELREF-3	2	2560	3270	3750	4210	5930	5.25
DELREF-3	3	2320	3110	3770	4530	5620	5.12
DELREF-4	1	2310	2690	3750	5020	5480	4.95
DELREF-4	2	1860	3240	3710	4470	5380	5.14
DELREF-4	3	1850	3000	3610	4370	5310	4.80
DELSDY	1	1580	2530	3230	4240	5320	5.57
DELSDY	2	1570	2430	3250	4170	5160	5.11
DELSDY	3	1710	2500	2940	4280	5220	5.74
DELSDY	1	1450	2700	3570	4350	5090	5.06
DELSDY	2	1760	2920	3200	4430	4740	--
DELSDY	3	1850	2270	3710	4330	4600	5.41
DELSDY	1	2190	3060	3180	4440	5310	5.47
DELSDY	2	2230	2730	3450	4540	5540	5.33
DELSDY	3	1930	2950	3540	4280	5420	5.12

(Continued)

[1] -- indicates test was not conducted on this batch.

Table B1 (Concluded)

Mixture	Batch No.	Compressive Strength, psi					28-day Modulus of Elasticity, 10^6 psi
		1-day	3-day	7-day	28-day	6-month	
DELSDY	1	2070	3340	3930	4720	5780	4.96
DELSDY	2	2250	3310	3980	4280	5590	5.06
DELSDY	3	2510	3470	3930	4950	5460	5.25
DELOVN	1	1670	2480	--	3500	4780	4.46
DELOVN	2	2040	3010	3820	4510	5940	4.44
DELOVN	3	1800	3180	--	4600	5980	5.55
DELOVN	1	2230	3330	4600	4810	5700	5.31
DELOVN	2	2020	3050	3610	4550	4880	4.56
DELOVN	3	2230	3330	3570	4600	5060	5.18
DELOVN	1	2750	--	4240	5730	6310	5.53
DELOVN	2	2480	3590	4070	4780	6190	5.42
DELOVN	3	2600	4210	4560	5800	6190	5.41
DELOVN	1	2590	4020	4690	4810	6190	5.16
DELOVN	2	2780	4170	4780	5360	6690	5.50
DELOVN	3	2760	3980	4690	5320	6370	5.54
DELLHL-1	1	1670	--	3200	4210	5090	5.60
DELLHL-1	2	1550	2720	3480	3980	5060	5.60
DELLHL-1	3	1860	2820	3540	4560	5410	5.70
DELLHL-2	1	2030	3160	3890	4790	5340	5.70
DELLHL-2	2	1980	2850	3890	4780	5060	5.00
DELLHL-2	3	2360	3780	4160	4810	5320	5.60
DELLHL-3	1	2020	3010	3680	4560	5590	5.70
DELLHL-3	2	2140	3110	3610	4350	5780	5.50
DELLHL-3	3	2130	2950	3750	4490	5800	5.50
DELLHL-4	1	2290	3250	3890	4420	5320	5.30
DELLHL-4	2	2480	3420	4090	4780	5890	5.50
DELLHL-4	3	2250	3530	4280	4990	6010	5.50

Table B2
Flexural Strength Test Results (Laboratory-Temperature Concrete)

Mixture	Batch No.	Flexural Strength, psi		
		3-day	7-day	28-day
DELREF-1	1	485	605	715
DELREF-1	2	495	615	655
DELREF-1	3	460	655	780
DELREF-2	1	590	620	710
DELREF-2	2	555	650	705
DELREF-2	3	580	615	635
DELREF-3	1	665	700	870
DELREF-3	2	585	665	750
DELREF-3	3	575	645	665
DELREF-4	1	--[1]	640	665
DELREF-4	2	540	660	750
DELREF-4	3	605	670	685
DELSDY-1	1	450	575	805
DELSDY-1	2	510	550	760
DELSDY-1	3	465	555	695
DELSDY-2	1	515	715	745
DELSDY-2	2	530	670	740
DELSDY-2	3	575	590	625
DELSDY-3	1	570	580	725
DELSDY-3	2	570	--	705
DELSDY-3	3	540	675	720
DELSDY-4	1	670	--	735
DELSDY-4	2	695	725	740
DELSDY-4	3	600	735	785

(Continued)

[1] -- indicates test was not conducted on this batch.

Table B2 (Concluded)				
Mixture	Batch No.	Flexural Strength, psi		
		3-day	7-day	28-day
DELOVN-1	1	520	590	665
DELOVN-1	2	635	690	790
DELOVN-1	3	535	715	890
DELOVN-2	1	540	655	655
DELOVN-2	2	560	635	620
DELOVN-2	3	570	660	710
DELOVN-3	1	730	830	890
DELOVN-3	2	705	750	955
DELOVN-3	3	--	780	880
DELOVN-4	1	710	725	810
DELOVN-4	2	715	750	815
DELOVN-4	3	725	795	835
DELLHL-1	1	--	600	790
DELLHL-1	2	400	630	650
DELLHL-1	3	530	670	770
DELLHL-2	1	580	720	710
DELLHL-2	2	630	650	665
DELLHL-2	3	630	--	705
DELLHL-3	1	570	675	845
DELLHL-3	2	535	745	845
DELLHL-3	3	515	735	800
DELLHL-4	1	680	745	770
DELLHL-4	2	675	--	735
DELLHL-4	3	675	750	825

Table B3
Rapid Freezing-and-Thawing Results
(Laboratory-Temperature Concrete)

Mixture	Batch No.	Durability Factor
DELREF-1	1	86
DELREF-1	2	88
DELREF-1	3	85
DELREF-2	1	88
DELREF-2	2	85
DELREF-2	3	85
DELREF-3	1	91
DELREF-3	2	90
DELREF-3	3	90
DELREF-4	1	93
DELREF-4	2	85
DELREF-4	3	90
DELSDY-1	1	86
DELSDY-1	2	83
DELSDY-1	3	86
DELSDY-2	1	89
DELSDY-2	2	88
DELSDY-2	3	80
DELSDY-3	1	88
DELSDY-3	2	87
DELSDY-3	3	94

(Continued)

Appendix B   Individual Compressive-Strength Test Results and Modulus-of-Elasticity Values

Table B3 (Concluded)

Mixture	Batch No.	Durability Factor
DELSDY-4	1	86
DELSDY-4	2	87
DELSDY-4	3	90
DELOVN-1	1	89
DELOVN-1	2	80
DELOVN-1	3	83
DELOVN-2	1	71
DELOVN-2	2	65
DELOVN-2	3	71
DELOVN-3	1	90
DELOVN-3	2	94
DELOVN-3	3	91
DELOVN-4	1	77
DELOVN-4	2	62
DELOVN-4	3	67
DELLHL-1	1	91
DELLHL-1	2	93
DELLHL-1	3	91
DELLHL-2	1	90
DELLHL-2	2	94
DELLHL-2	3	91
DELLHL-3	1	93
DELLHL-3	2	94
DELLHL-3	3	94
DELLHL-4	1	--[1]
DELLHL-4	2	90
DELLHL-4	3	89

[1] -- indicates test was not conducted for this batch.

Appendix B   Individual Compressive-Strength Test Results and Modulus-of-Elasticity Values

Table B4
Length-Change Test Results
(Laboratory-Temperature Concrete)

Mixture	Batch No.	Length Change, percent
DELREF-1	1	-0.021
DELREF-1	2	-0.009
DELREF-1	3	-0.023
DELREF-2	1	-0.027
DELREF-2	2	-0.033
DELREF-2	3	-0.037
DELREF-3	1	-0.010
DELREF-3	2	-0.034
DELREF-3	3	-0.017
DELREF-4	1	-0.026
DELREF-4	2	-0.025
DELREF-4	3	-0.028
DELSDY-1	1	-0.030
DELSDY-1	2	-0.025
DELSDY-1	3	-0.022
DELSDY-2	1	-0.027
DELSDY-2	2	-0.031
DELSDY-2	3	-0.025
DELSDY-3	1	-0.011
DELSDY-3	2	--[1]
DELSDY-3	3	-0.019
DELSDY-4	1	-0.047
DELSDY-4	2	-0.027
DELSDY-4	3	-0.029

(Continued)

[1] -- indicates test was not conducted for this batch.

Table B4 (Concluded)

Mixture	Batch No.	Length Change, percent
DELOVN-1	1	-0.044
DELOVN-1	2	-0.037
DELOVN-1	3	-0.037
DELOVN-2	1	-0.038
DELOVN-2	2	-0.040
DELOVN-2	3	-0.049
DELOVN-3	1	-0.024
DELOVN-3	2	-0.034
DELOVN-3	3	-0.028
DELOVN-4	1	-0.040
DELOVN-4	2	-0.048
DELOVN-4	3	-0.039
DELLHL-1	1	-0.023
DELLHL-1	2	-0.023
DELLHL-1	3	-0.026
DELLHL-2	1	-0.037
DELLHL-2	2	-0.026
DELLHL-2	3	-0.026
DELLHL-3	1	-0.026
DELLHL-3	2	-0.022
DELLHL-3	3	-0.030
DELLHL-4	1	-0.032
DELLHL-4	2	-0.024
DELLHL-4	3	-0.023

Table B5
Chloride-Ion Penetration Test Results
(Laboratory-Temperature Concrete)

Mixture	Batch No.	Charge Passed, coulombs
DELREF-1	1	3170
DELREF-1	2	3150
DELREF-1	3	3130
DELREF-2	1	5090
DELREF-2	2	4790
DELREF-2	3	4800
DELREF-3	1	4710
DELREF-3	2	3860
DELREF-3	3	4020
DELREF-4	1	4200
DELREF-4	2	5640
DELREF-4	3	6990
DELSDY-1	1	3910
DELSDY-1	2	2630
DELSDY-1	3	3200
DELSDY-2	1	3880
DELSDY-2	2	4430
DELSDY-2	3	4760
DELSDY-3	1	3410
DELSDY-3	2	3460
DELSDY-3	3	3000
DELSDY-4	1	3320
DELSDY-4	2	3680
DELSDY-4	3	4830

(Sheet 1 of 3)

Table B5 (Continued)		
Mixture	Batch No.	Charge Passed, coulombs
DELOVN-1	1	4425
DELOVN-1	2	--[1]
DELOVN-1	3	4185
DELOVN-2	1	5250
DELOVN-2	2	8180
DELOVN-2	3	7580
DELOVN-3	1	2470
DELOVN-3	2	3950
DELOVN-3	3	2800
DELOVN-4	1	5110
DELOVN-4	2	4040
DELOVN-4	3	5760
DELLHL-1	1	3100
DELLHL-1	2	3130
DELLHL-1	3	2710
DELLHL-2	1	4430
DELLHL-2	2	4640
DELLHL-2	3	3990
DELLHL-3	1	3260
DELLHL-3	2	2950
DELLHL-3	3	3160
DELLHL-4	1	4330
DELLHL-4	2	4110
DELLHL-4	3	4290
DELREFH-1	1	4350
DELREFH-1	2	3030
DELREFH-1	3	4500
		(Sheet 2 of 3)

[1] -- indicates test was not conducted for this batch.

Appendix B   Individual Compressive-Strength Test Results and Modulus-of-Elasticity Values

Table B5 (Concluded)		
Mixture	Batch No.	Charge Passed, coulombs
DELREFH-2	1	5420
DELREFH-2	2	3700
DELREFH-2	3	4870
DELSDYH-1	1	2900
DELSDYH-1	2	2910
DELSDYH-1	3	3320
DELSDYH-2	1	3710
DELSDYH-2	2	4320
DELSDYH-2	3	4640
		(Sheet 3 of 3)

Table B6
Compressive-Strength and Modulus-of-Elasticity Test Results
(Elevated-Temperature Concrete)

Mixture	Batch No.	Compressive Strength, psi					28-day Modulus of Elasticity, 10^6 psi
		1-day	3-day	7-day	28-day	6-month	
DELREFH-1	1	1700	2120	2480	3890	4780	5.05
DELREFH-1	2	1630	2880	3310	4350	5230	6.26
DELREFH-1	3	1820	2640	3380	4130	5520	5.32
DELREFH-2	1	1870	2510	3860	4300	5180	4.97
DELREFH-2	2	1830	3290	3780	4650	5220	5.97
DELREFH-2	3	1790	3180	3780	4920	5220	4.77
DELSDY-1	1	1850	3020	3190	4600	5940	5.35
DELSDY-1	2	1650	2540	3040	4000	5310	5.90
DELSDY-1	3	1720	2560	3270	4210	5500	6.12
DELSDY-2	1	1630	3170	3590	4140	4560	5.23
DELSDY-2	2	1560	3220	3680	4100	4930	4.95
DELSDY-2	3	1820	3220	3040	4170	4950	5.13

Appendix B   Individual Compressive-Strength Test Results and Modulus-of-Elasticity Values

Table B7
Flexural-Strength Test Results
(Elevated-Temperature Concrete)

Mixture	Batch No.	Flexural Strength, psi		
		3-day	7-day	28-day
DELREFH-1	1	390	535	650
DELREHF-1	2	--	625	770
DELREHF-1	3	465	585	650
DELREHF-2	1	515	650	750
DELREHF-2	2	575	715	735
DELREHF-2	3	--	640	760
DELSDHY-1	1	550	645	770
DELSDHY-1	2	530	605	675
DELSDHY-1	3	510	605	750
DELSDHY-2	1	610	690	720
DELSDHY-2	2	610	665	780
DELSDHY-2	3	580	630	725

Table B8 Rapid Freezing-and-Thawing Results (Elevated-Temperature Concrete)		
Mixture	Batch No.	Durability Factor
DELREFH-1	1	80
DELREFH-1	2	85
DELREFH-1	3	84
DELREFH-2	1	83
DELREFH-2	2	82
DELREFH-2	3	89
DELSDYH-1	1	82
DELSDYH-1	2	91
DELSDYH-1	3	90
DELSDYH-2	1	86
DELSDYH-2	2	90
DELSDYH-2	3	92

Table B9
Length-Change Test Results
(Elevated-Temperature Concrete)

Mixture	Batch No.	Length Change, percent
DELREFH-1	1	-0.014
DELREFH-1	2	-0.015
DELREFH-1	3	-0.014
DELREFH-2	1	-0.023
DELREFH-2	2	-0.024
DELREFH-2	3	-0.028
DELSDYH-1	1	-0.027
DELSDYH-1	2	-0.019
DELSDYH-1	3	--[1]
DELSDYH-2	1	--
DELSDYH-2	2	--
DELSDYH-2	3	-0.035

[1] -- indicates test was not conducted for this batch.

Appendix B   Individual Compressive-Strength Test Results and Modulus-of-Elasticity Values

Table B10		
Chloride-Ion Penetration Test Results		
(Elevated-Temperature Concrete)		
Mixture	Batch No.	Length Change, percent
DELREFH-1	1	4350
DELREFH-1	2	3030
DELREFH-1	3	4500
DELREFH-2	1	5420
DELREFH-2	2	3700
DELREFH-2	3	4870
DELSDYH-1	1	2900
DELSDYH-1	2	2910
DELSDYH-1	3	3320
DELSDYH-2	1	3710
DELSDYH-2	2	4320
DELSDYH-2	3	4640

Appendix C
Failure Envelopes for Direct Shear
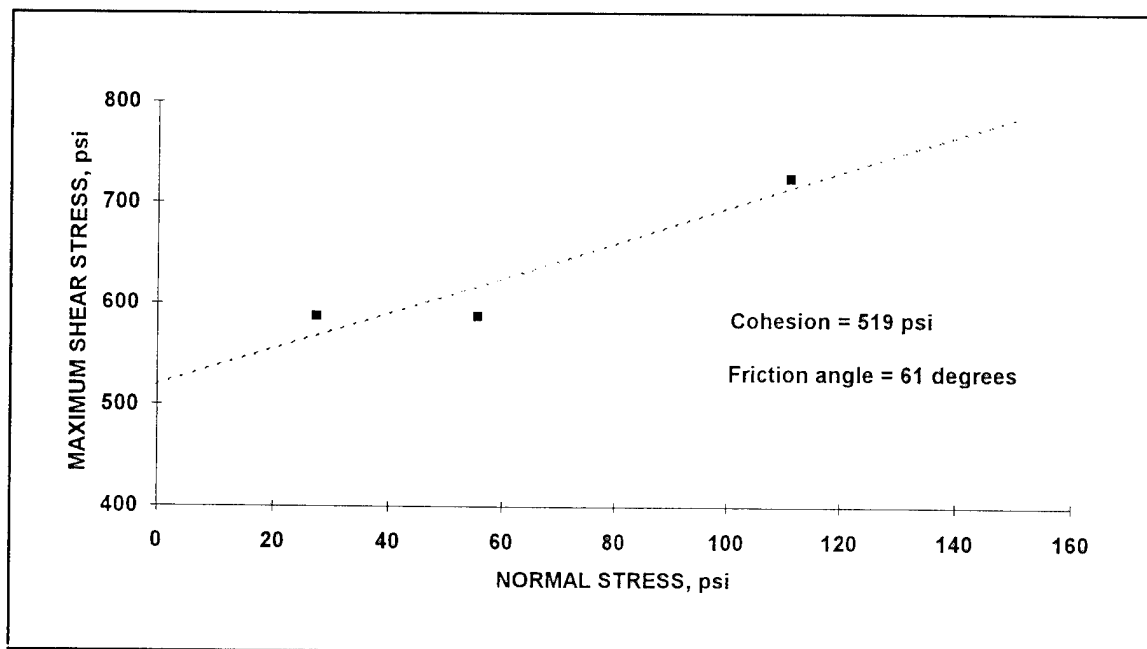
Figure C1. Direct-shear failure envelope representing laboratory joint condition no. 1-1
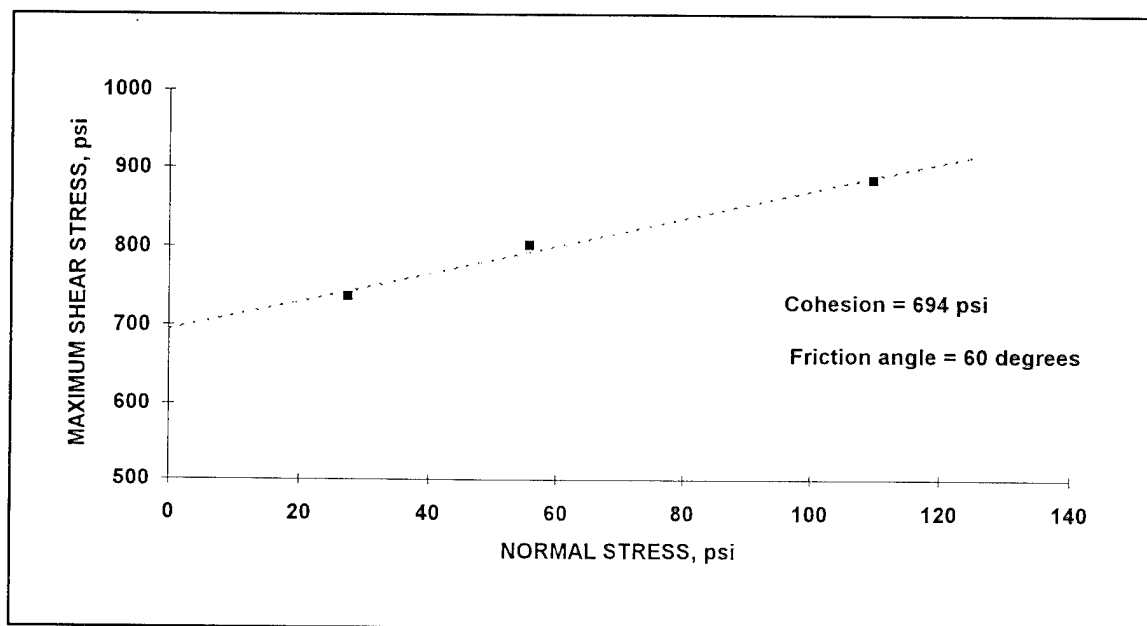
Figure C2. Direct-shear failure envelope representing laboratory joint condition no. 1-2

C2
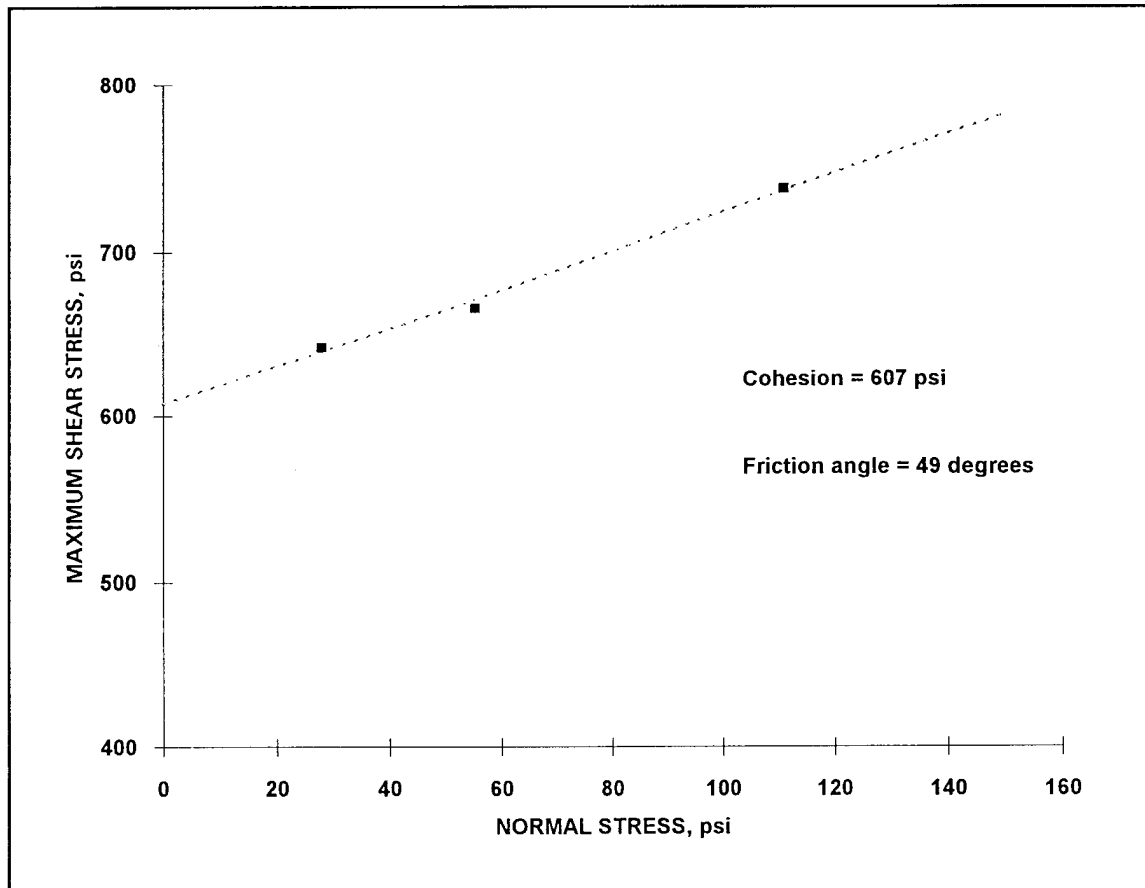
Figure C3.   Direct-shear failure envelope representing laboratory joint condition no. 1-3
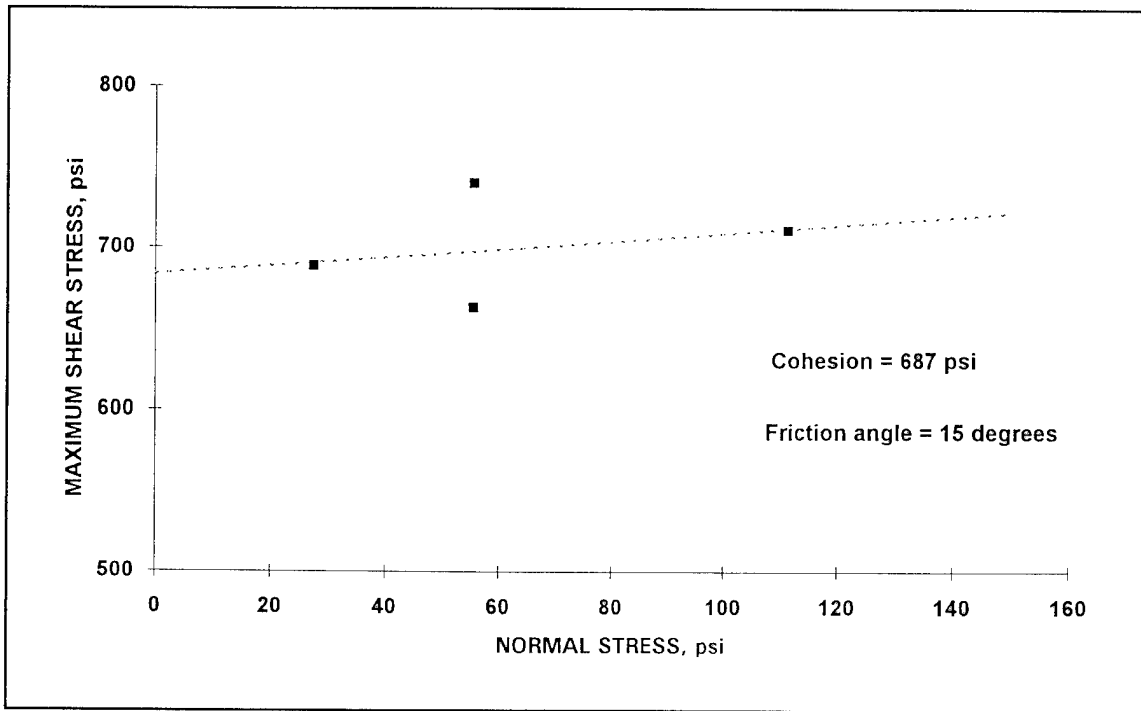
Figure C4.   Direct-shear failure envelope representing laboratory joint condition no. 1-4
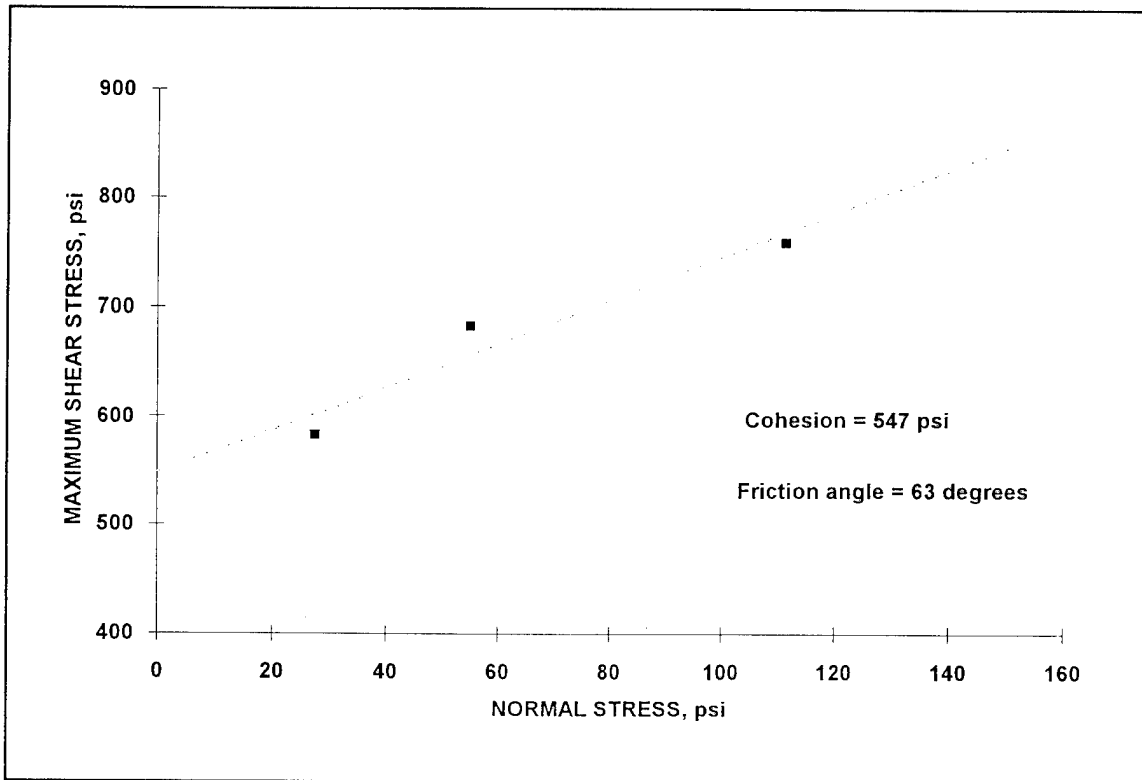
Figure C5.   Direct-shear failure envelope representing laboratory joint condition no. 1-5

Appendix C   Failure Envelopes for Direct Shear
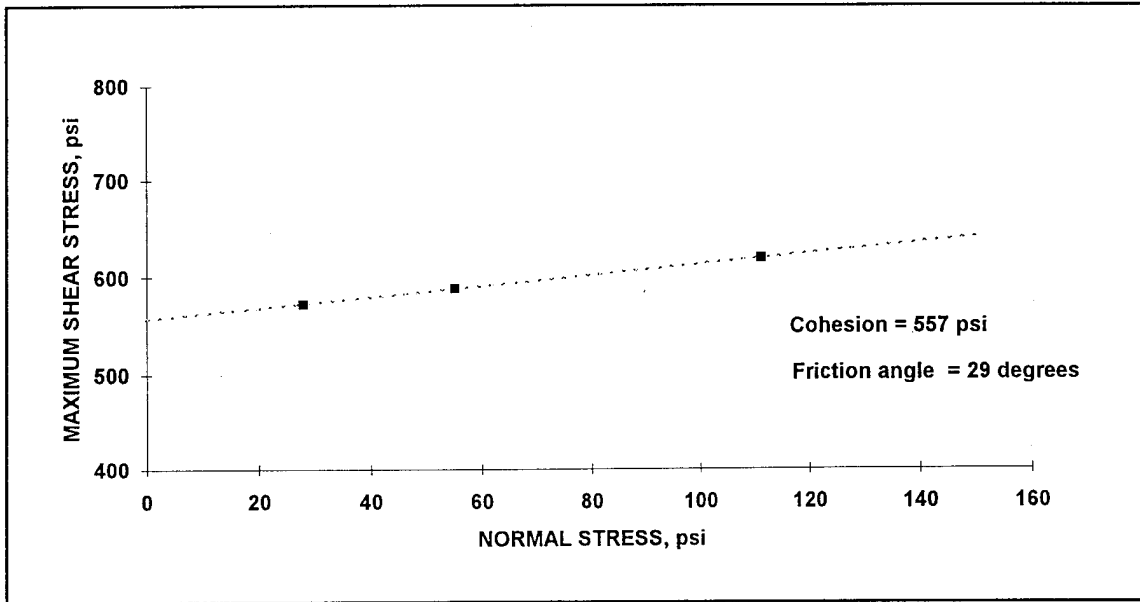
Figure C6.   Direct-shear failure envelope representing laboratory joint condition no. 1-6
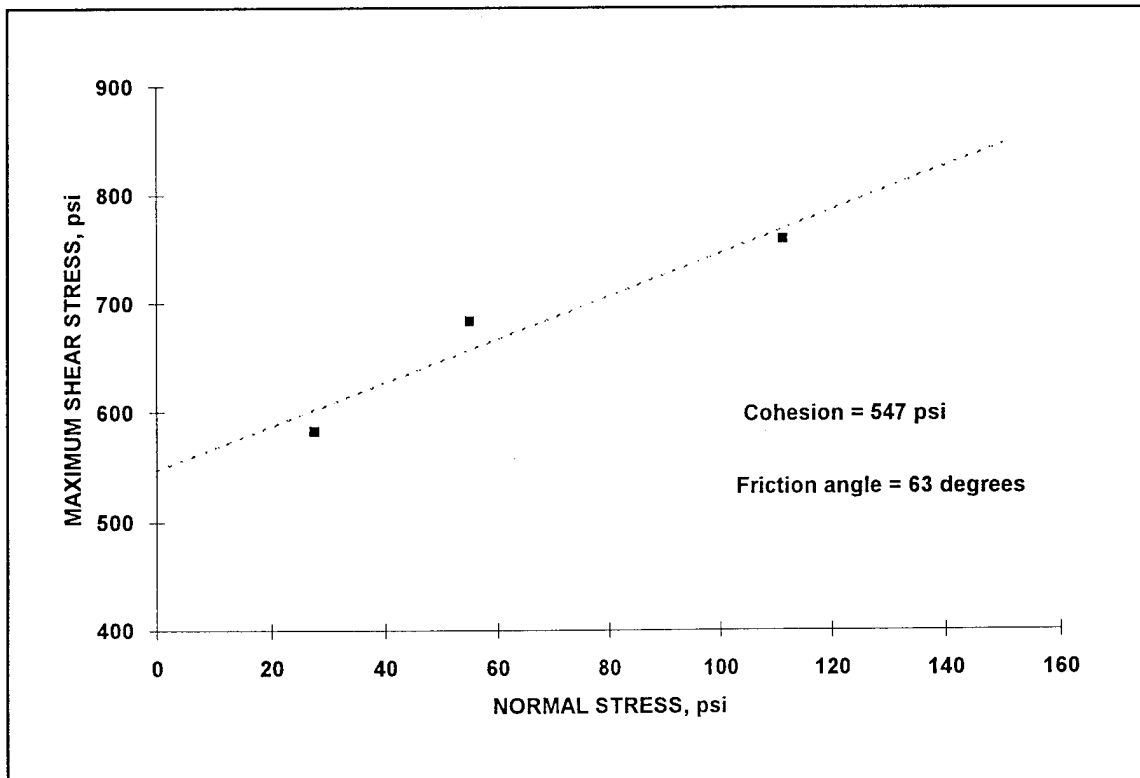
Figure C7.   Direct-shear failure envelope representing laboratory joint condition no. 1-7
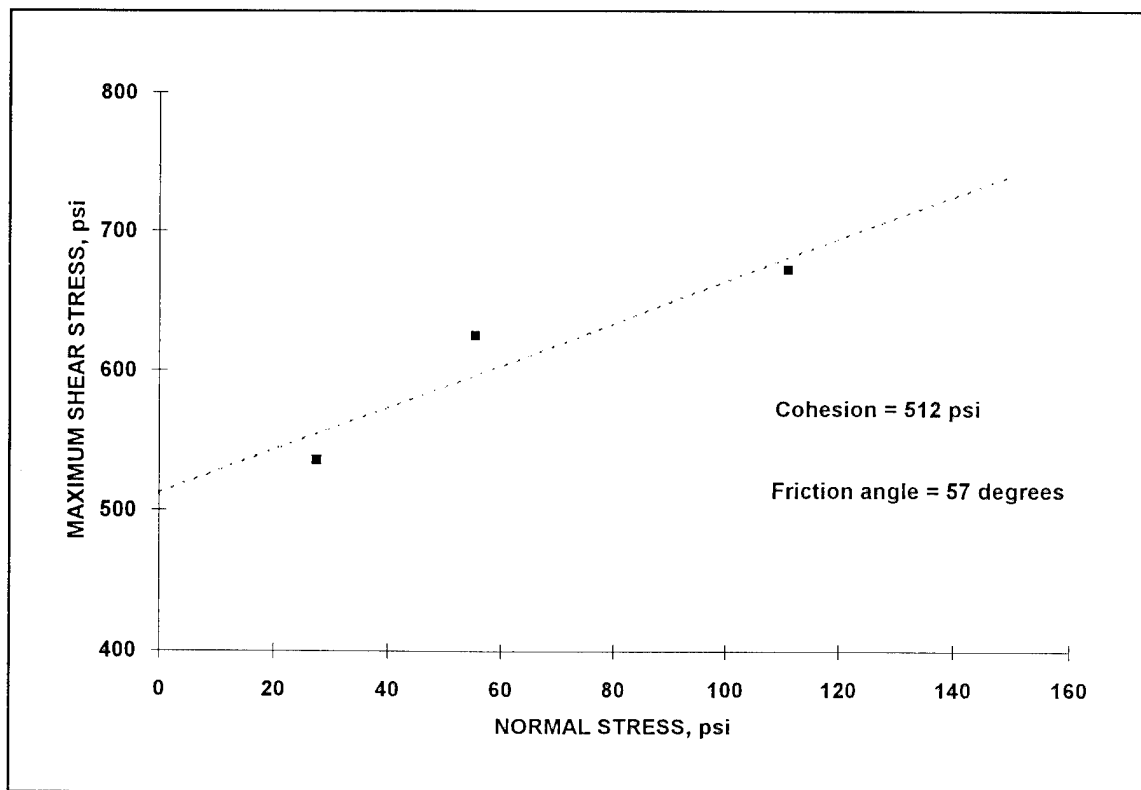
Figure C8.   Direct-shear failure envelope representing laboratory joint condition no. 1-8
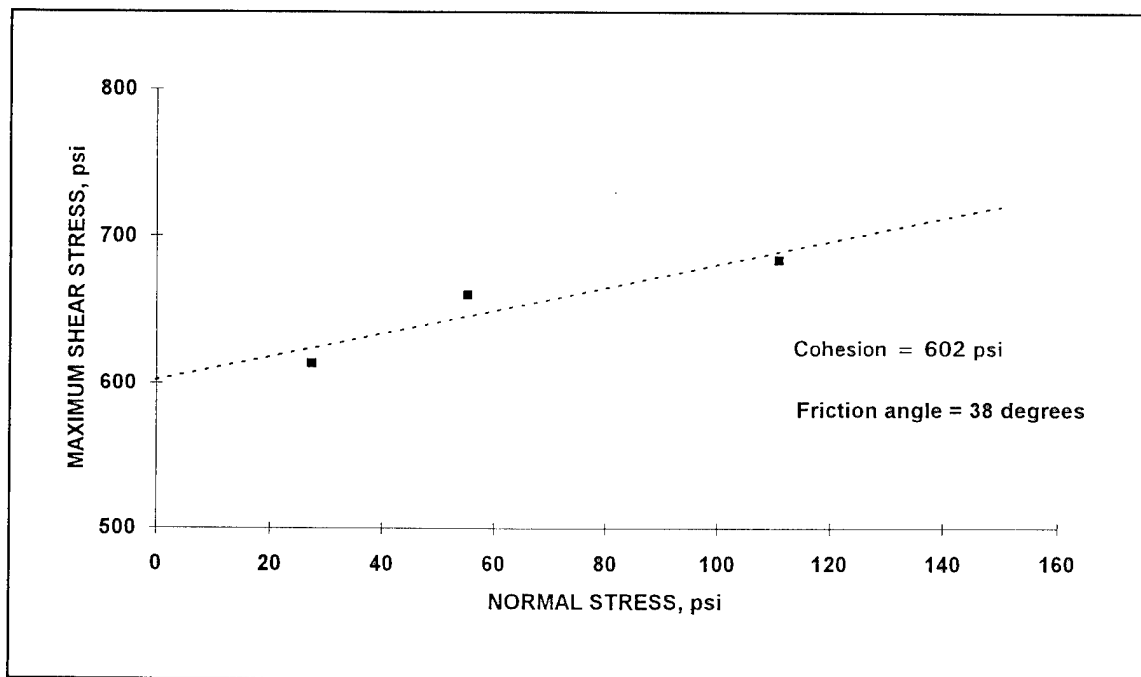
Figure C9.   Direct-shear failure envelope representing laboratory joint condition no. 2-1

C6
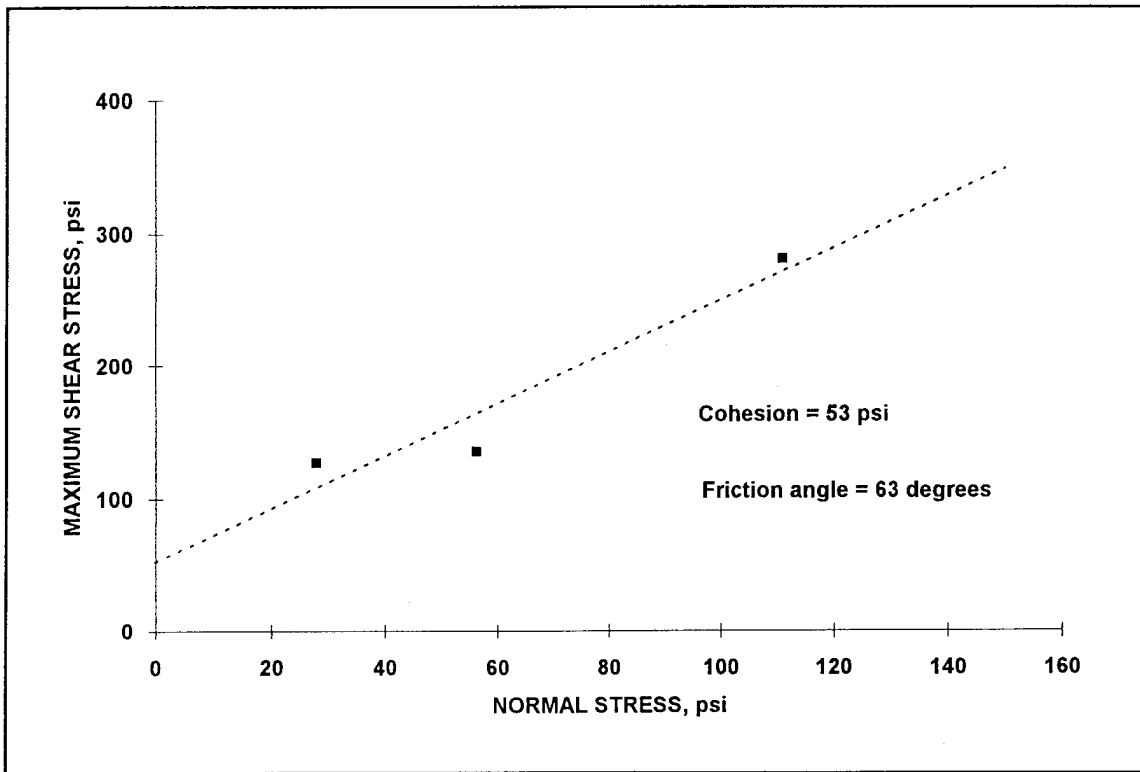
Figure C10. Direct-shear failure envelope representing laboratory joint condition no. 2-2
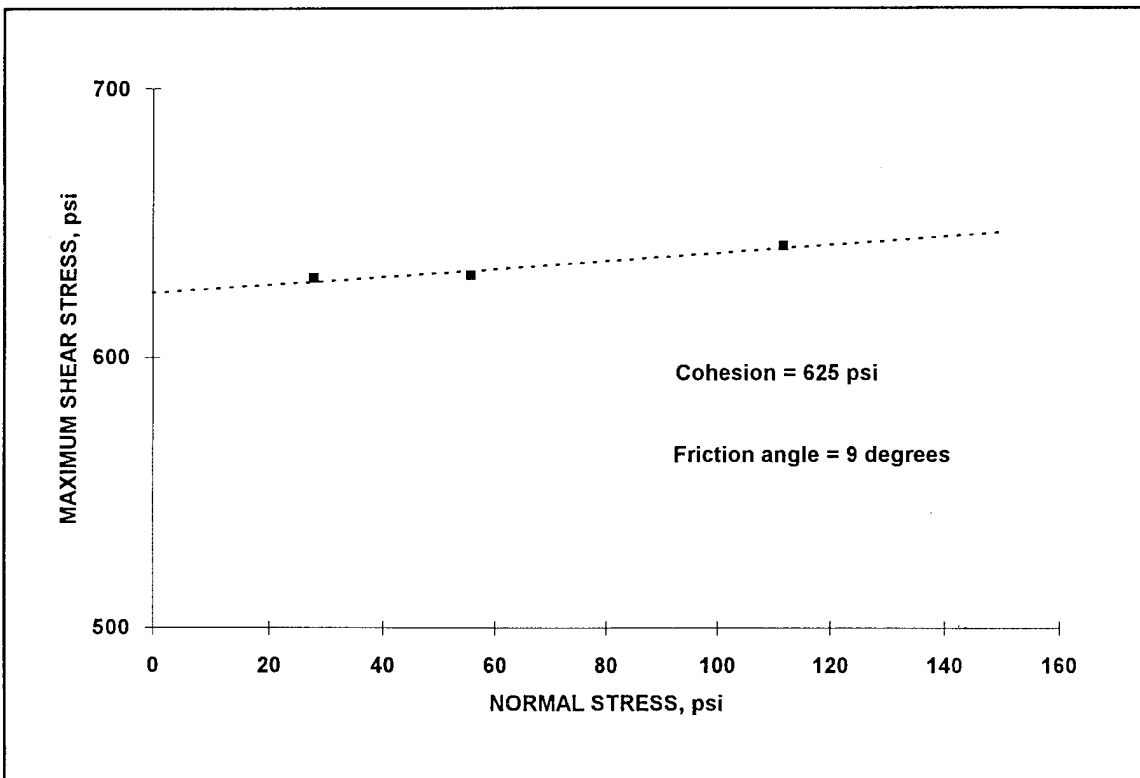
Figure C11. Direct-shear failure envelope representing laboratory joint condition no. 2-3
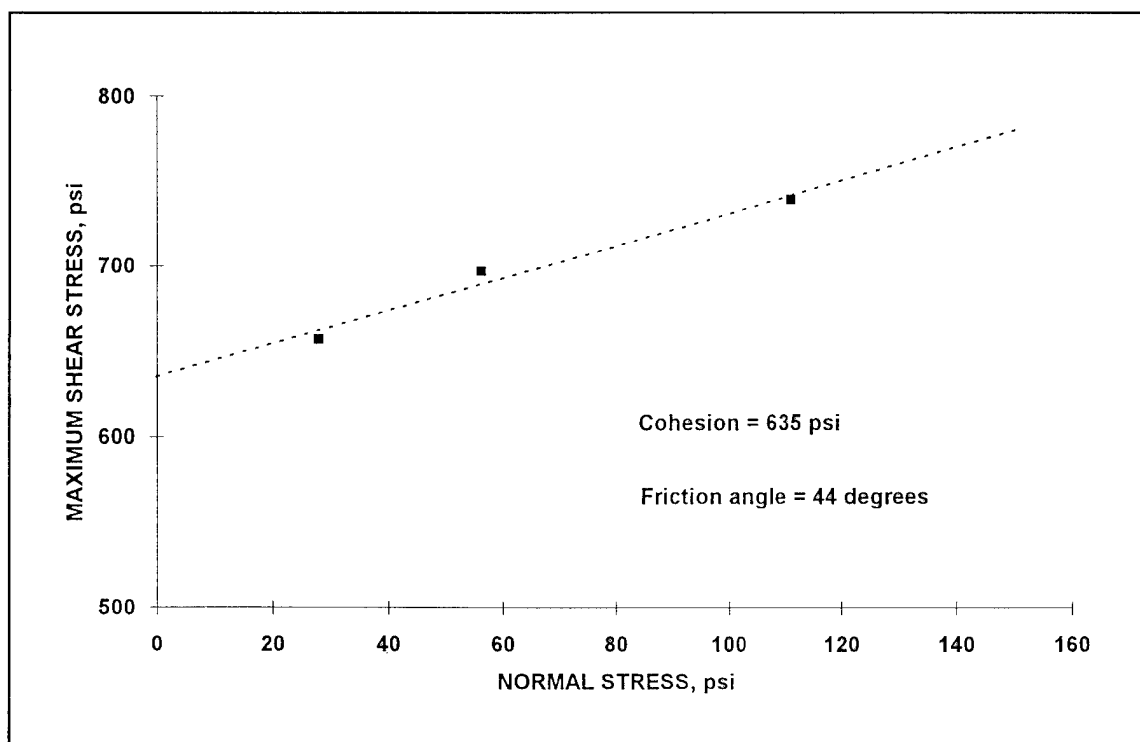
Figure C12. Direct-shear failure envelope representing laboratory joint condition no. 2-4
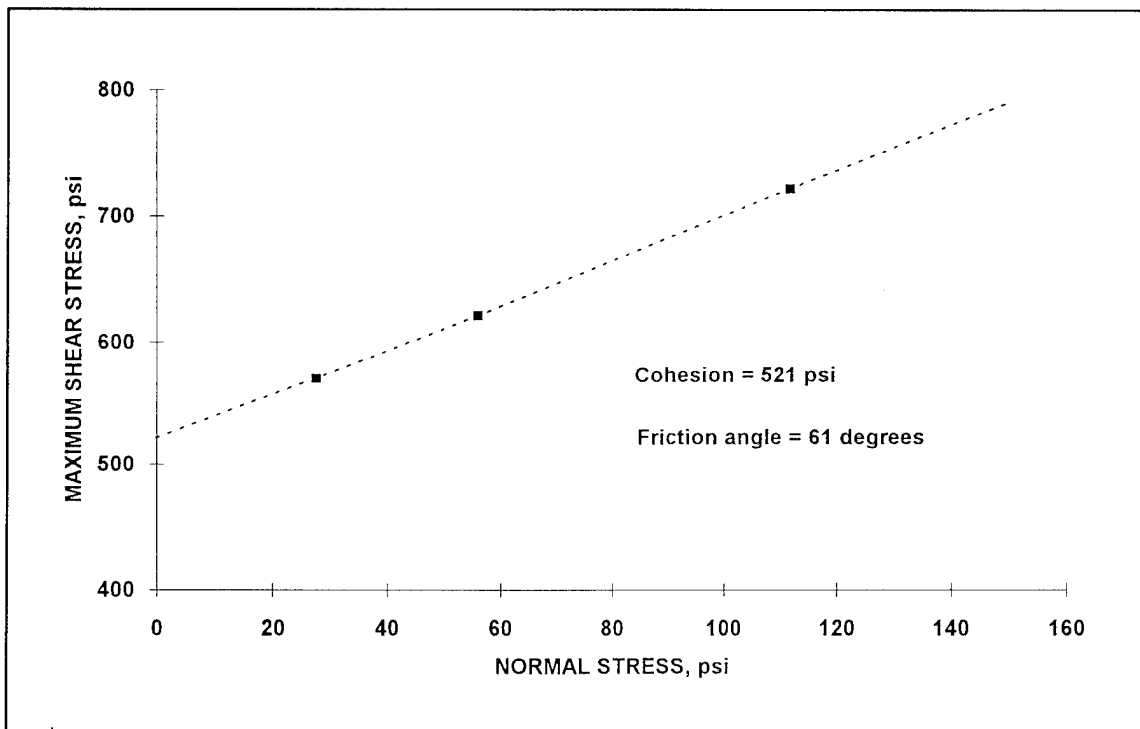
Figure C13. Direct-shear failure envelope representing laboratory joint condition no. 2-5

C8
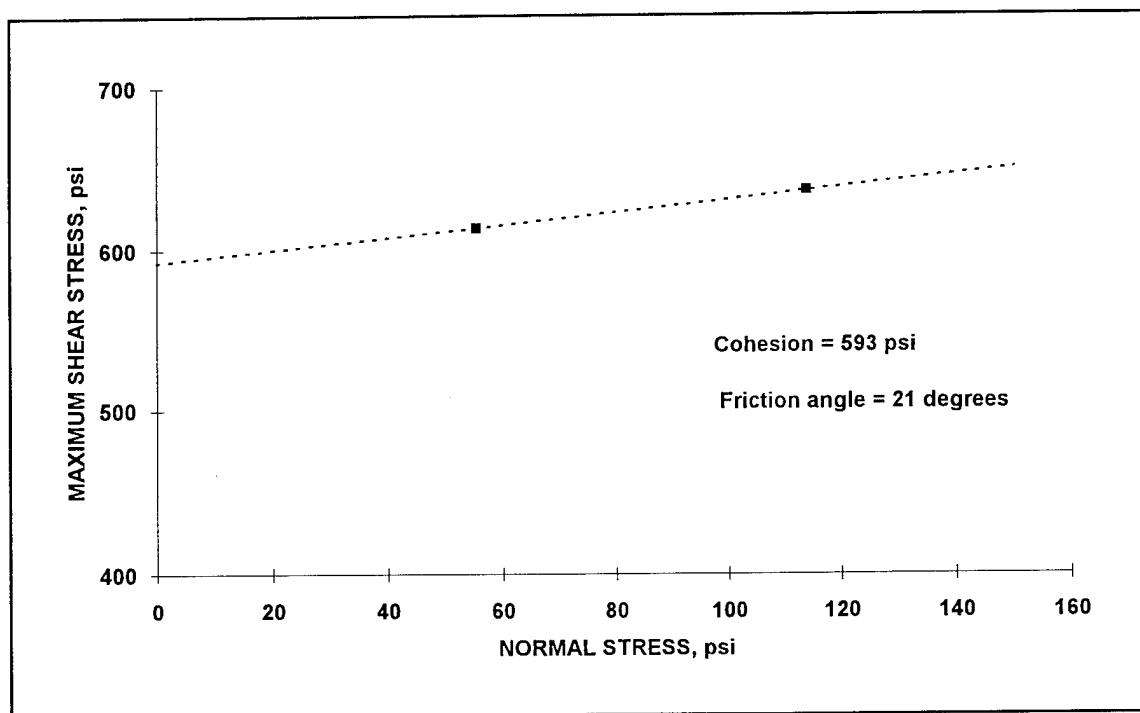
Figure C14. Direct-shear failure envelope representing laboratory joint condition no. 2-6
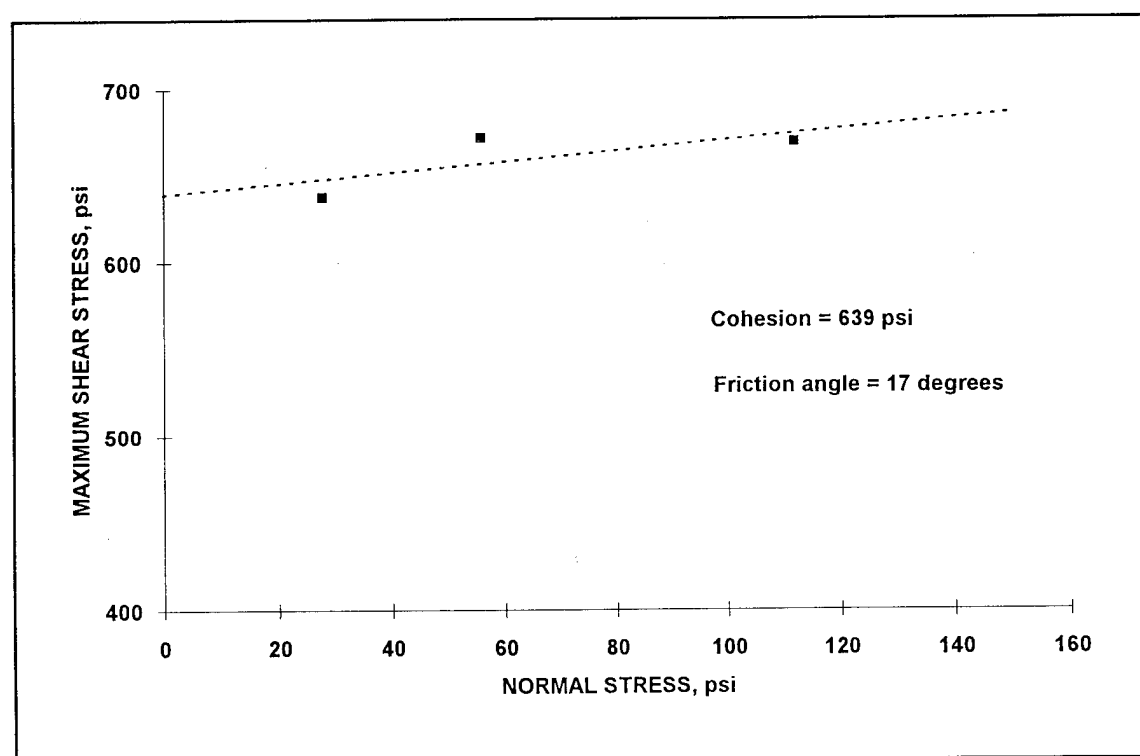
Figure C15. Direct-shear failure envelope representing laboratory joint condition no. 2-7
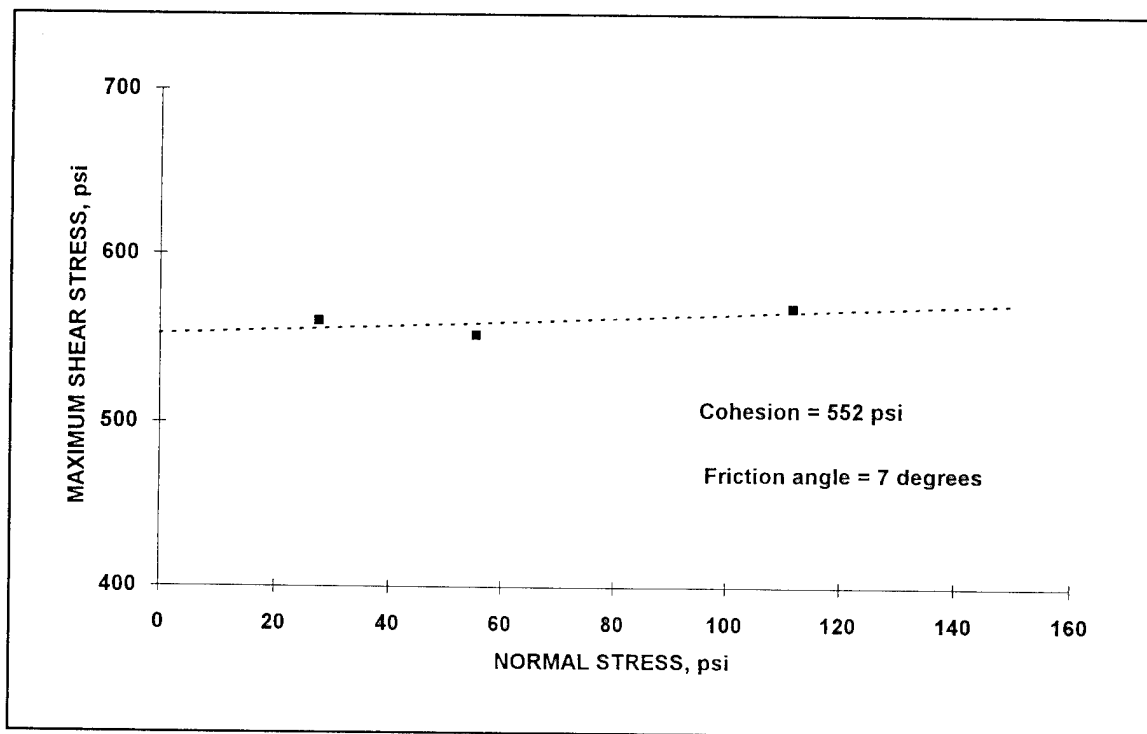
Figure C16. Direct-shear failure envelope representing laboratory joint condition no. 2-8
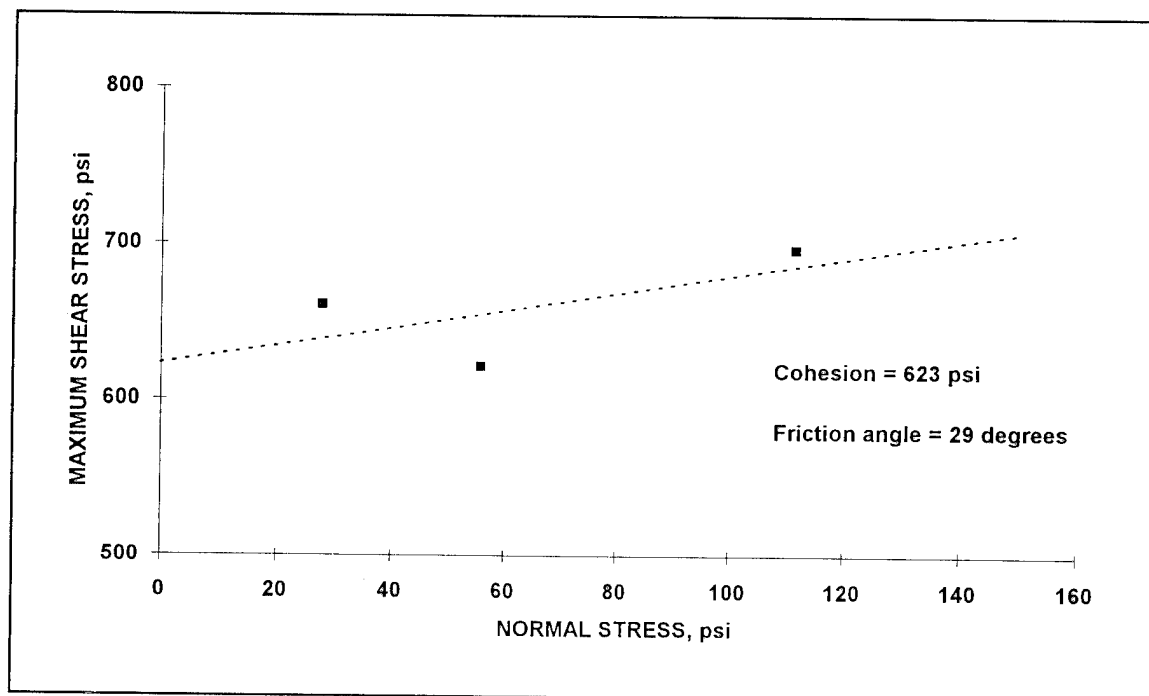
Figure C17. Direct-shear failure envelope representing laboratory joint condition no. 2-9

Appendix D
Compressive-Strength Development of Shotcrete Mixtures Monitored for 28 days
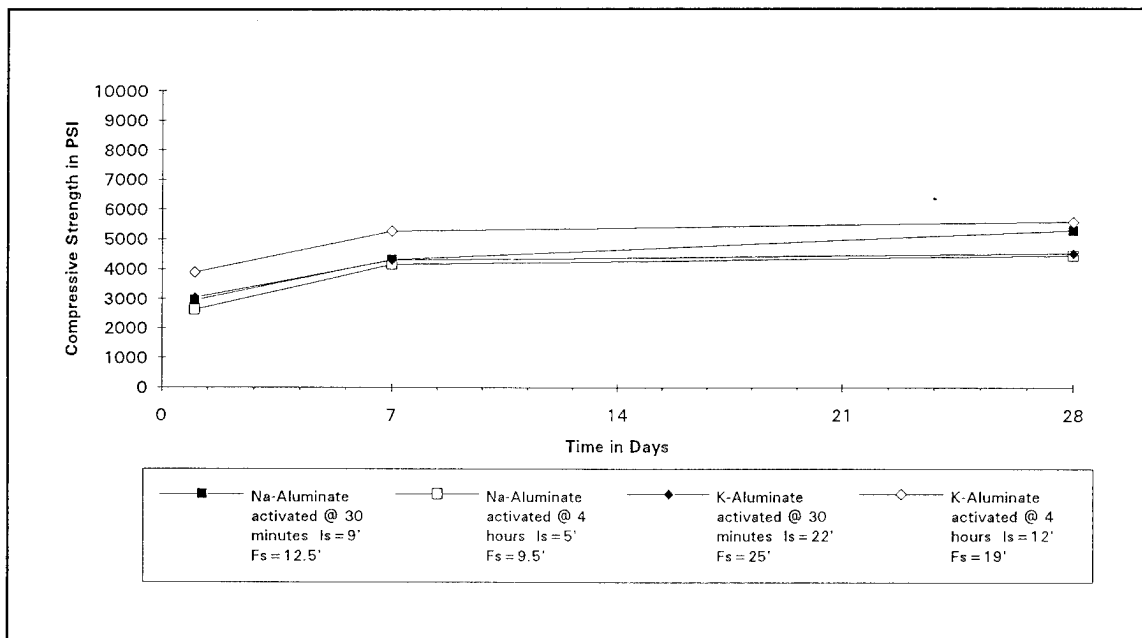
Figure D1.   Compressive-strength development of shotcrete containing Type I cement,
6-oz DELVOCRETE Stabilizer/100-lb cement, and 8-percent Activator by mass
of cement
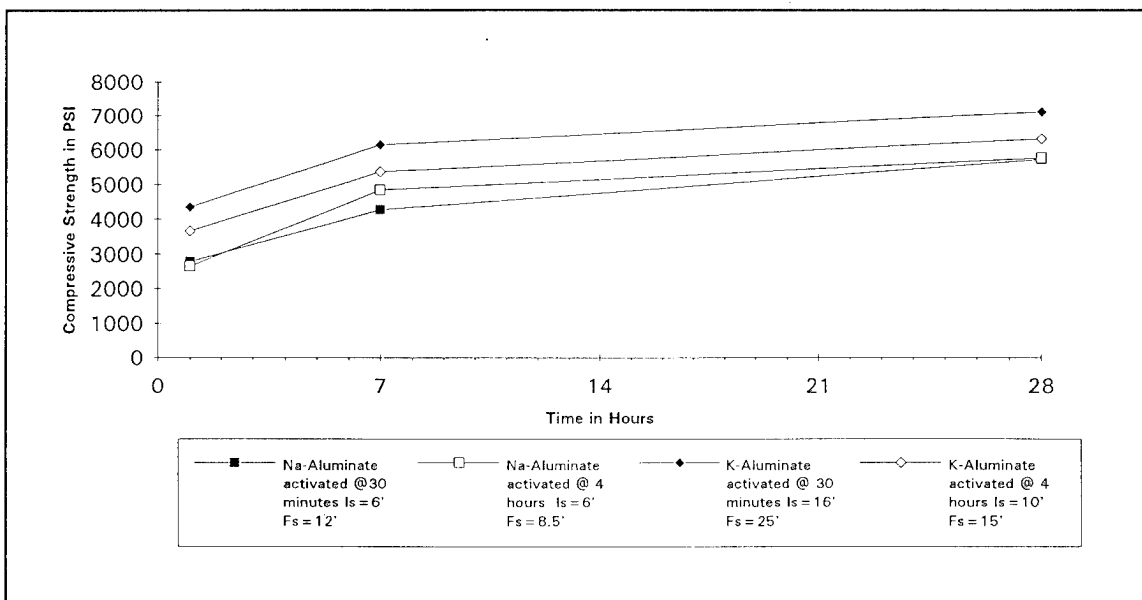
Figure D2.   Compressive-strength development of shotcrete containing Type I cement,
6-oz DELVOCRETE Stabilizer/100-lb cement, 6-percent Activator by mass of
cement
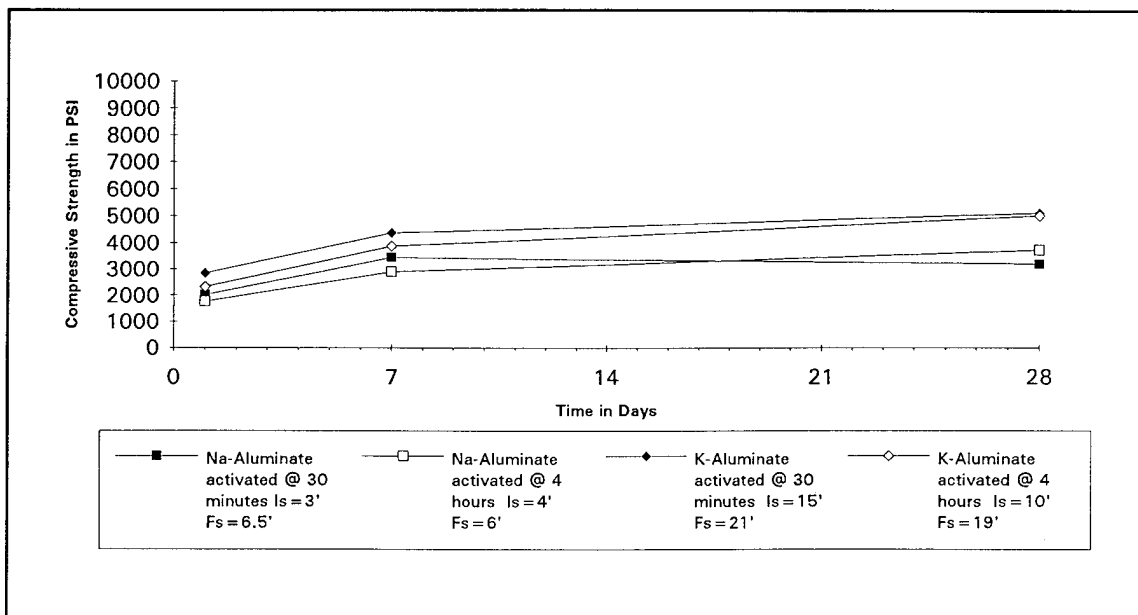
Figure D3. Compressive-strength development of shotcrete containing Type I cement, 6-oz DELVOCRETE Stabilizer/100-lb cement, 4-percent Activator by mass of cement
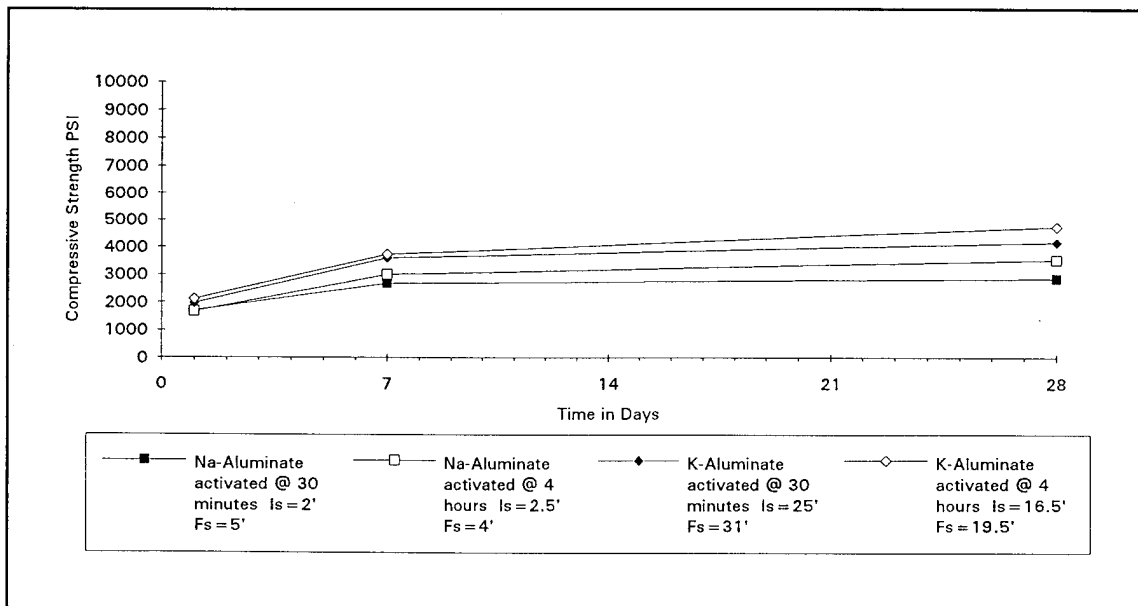
Figure D4. Compressive-strength development of shotcrete containing Type II cement, 6-oz DELVOCRETE Stabilizer/100-lb cement, 8-percent Activator by mass of cement
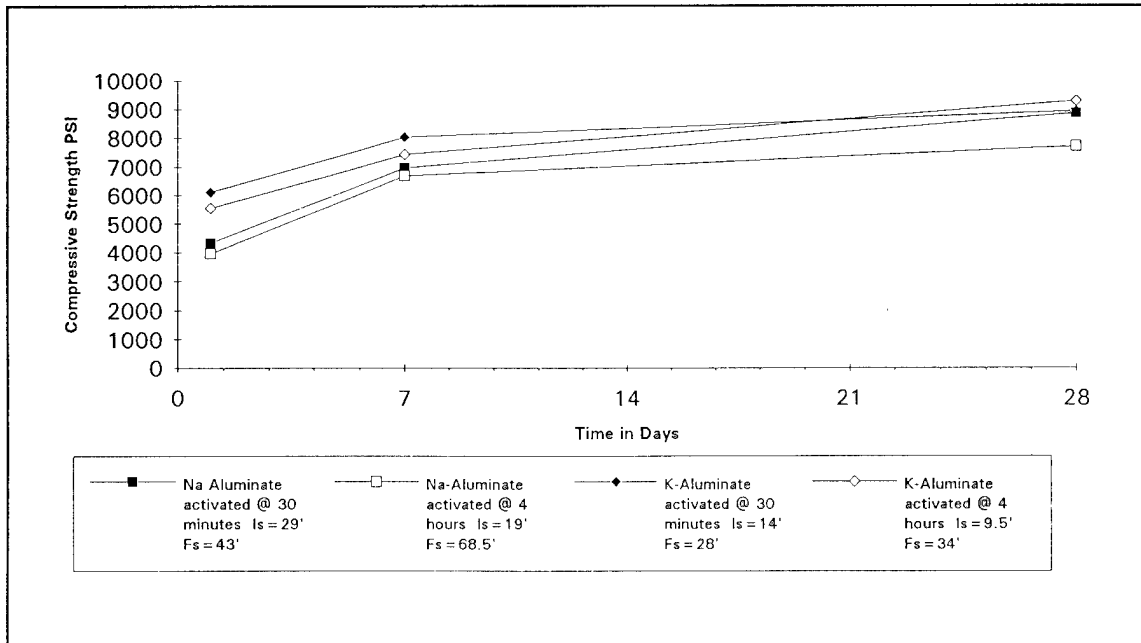
Figure D5. Compressive-strength development of shotcrete containing Type II cement, 6-oz DELVOCRETE Stabilizer/100-lb cement, 6-percent Activator by mass of cement
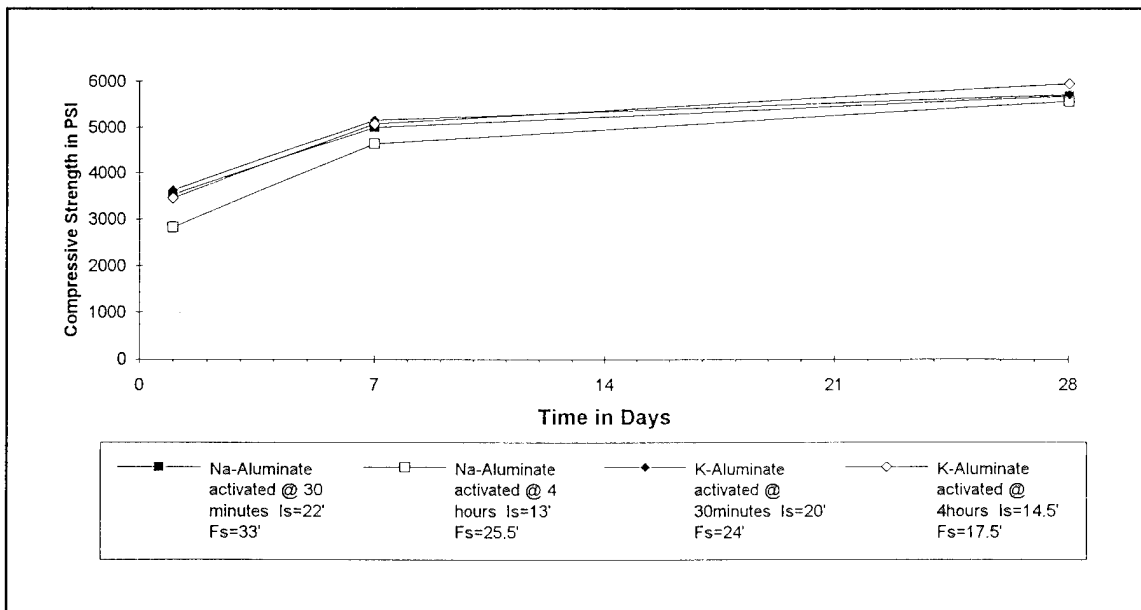
Figure D6. Compressive-strength development of shotcrete containing Type II cement, 6-oz DELVOCRETE Stabilizer/100-lb cement, 4-percent Activator percent by mass of cement
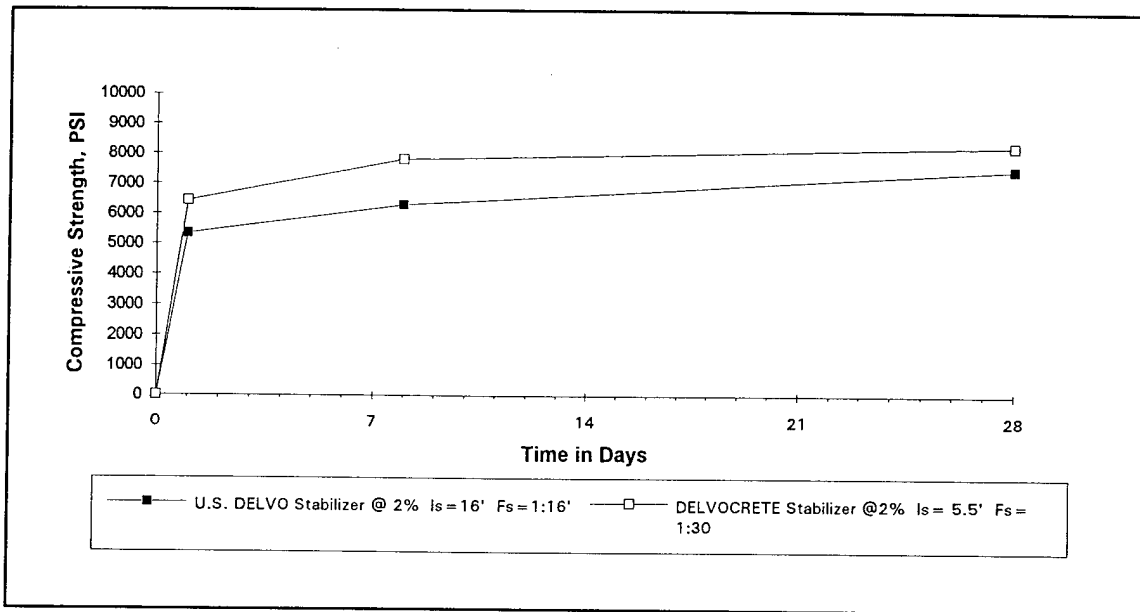
Figure D7. Compressive-strength development of shotcrete containing Type I cement activated at 48 hr with 4-percent S-71 by mass of cement
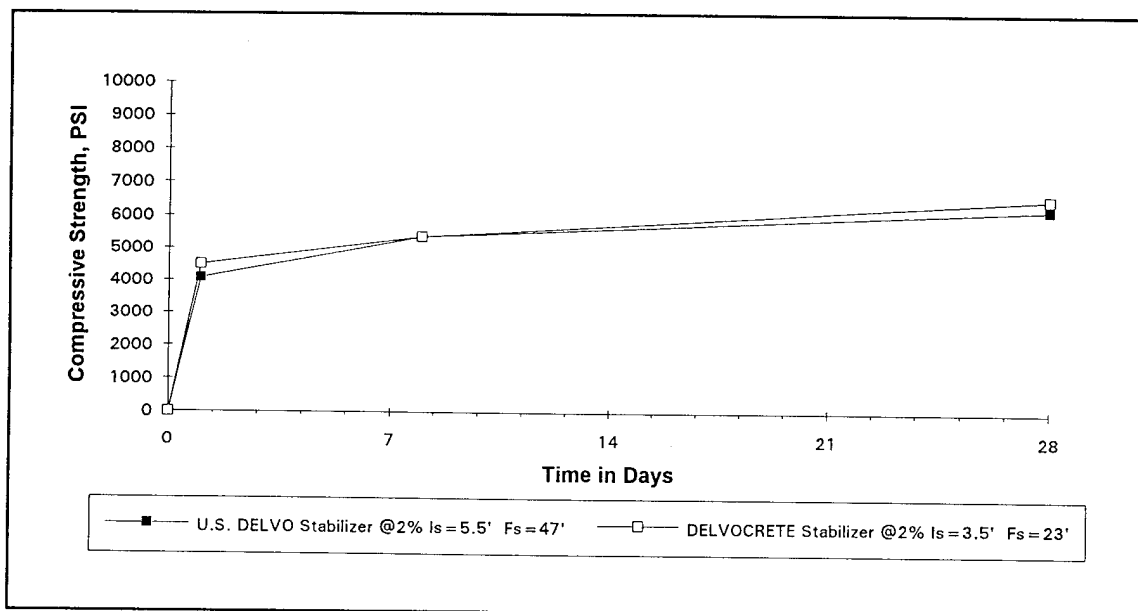
Figure D8. Compressive-strength development of shotcrete containing Type I cement activated at 48 hr with 6-percent S-71 by mass of cement
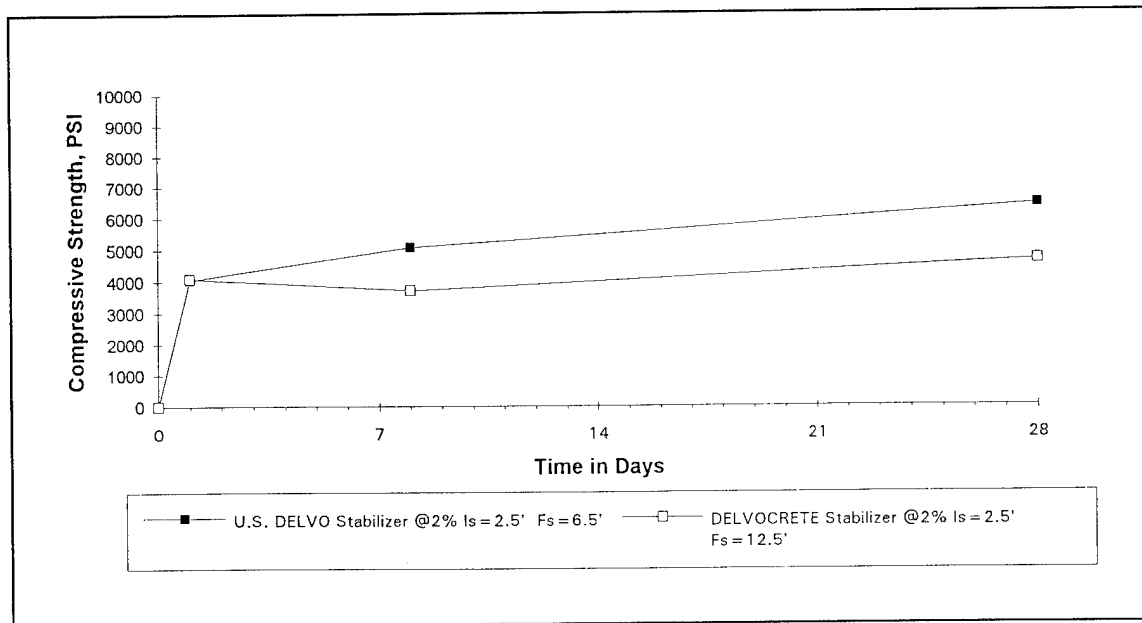
Figure D9. Compressive-strength development of shotcrete containing Type I cement activated at 48 hr with 8-percent S-71 by mass of cement
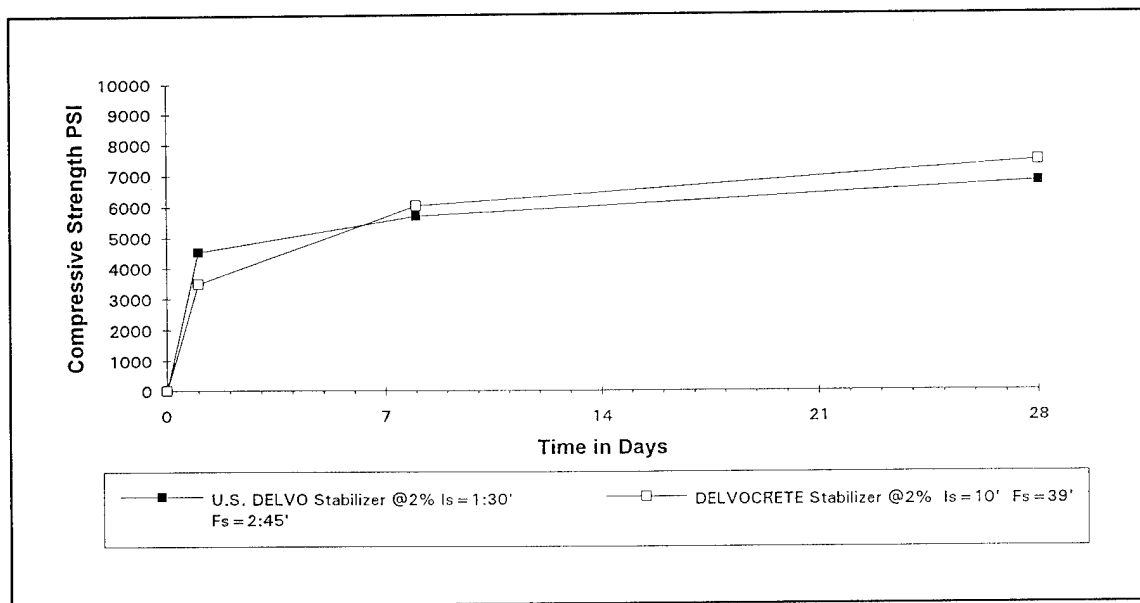
Figure D10. Compressive-strength development of shotcrete containing Type II cement activated at 48 hr with 4-percent S-71 by mass of cement
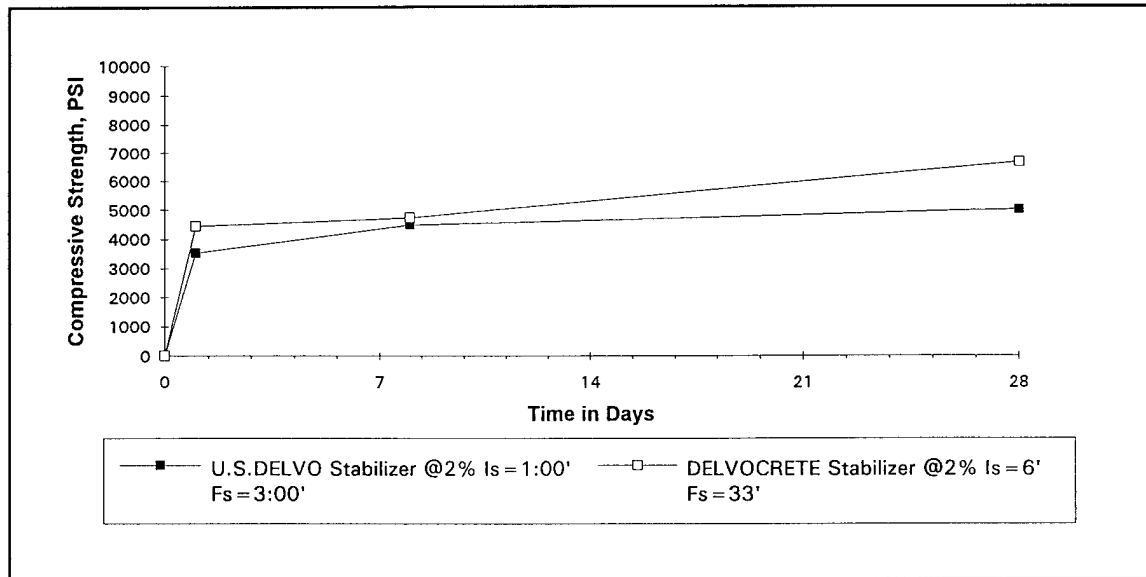
Figure D11. Compressive-strength development of shotcrete containing Type II cement activated at 48 hr with 6-percent S-71 by mass of cement
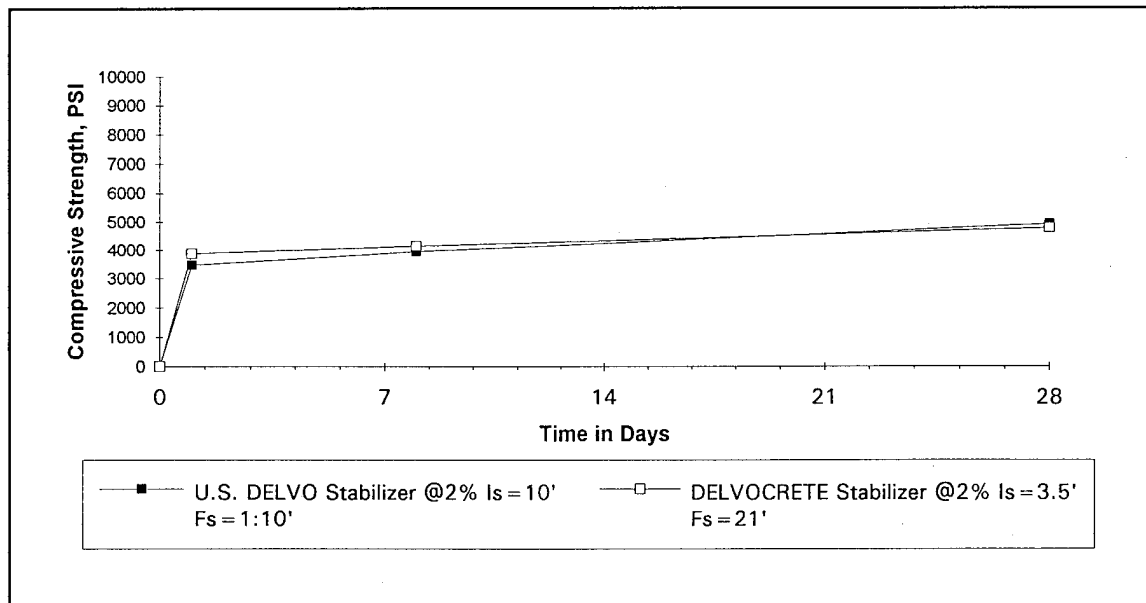
Figure D12. Compressive-strength development of shotcrete containing Type II cement activated at 48 hr with 8-percent S-71 by mass of cement
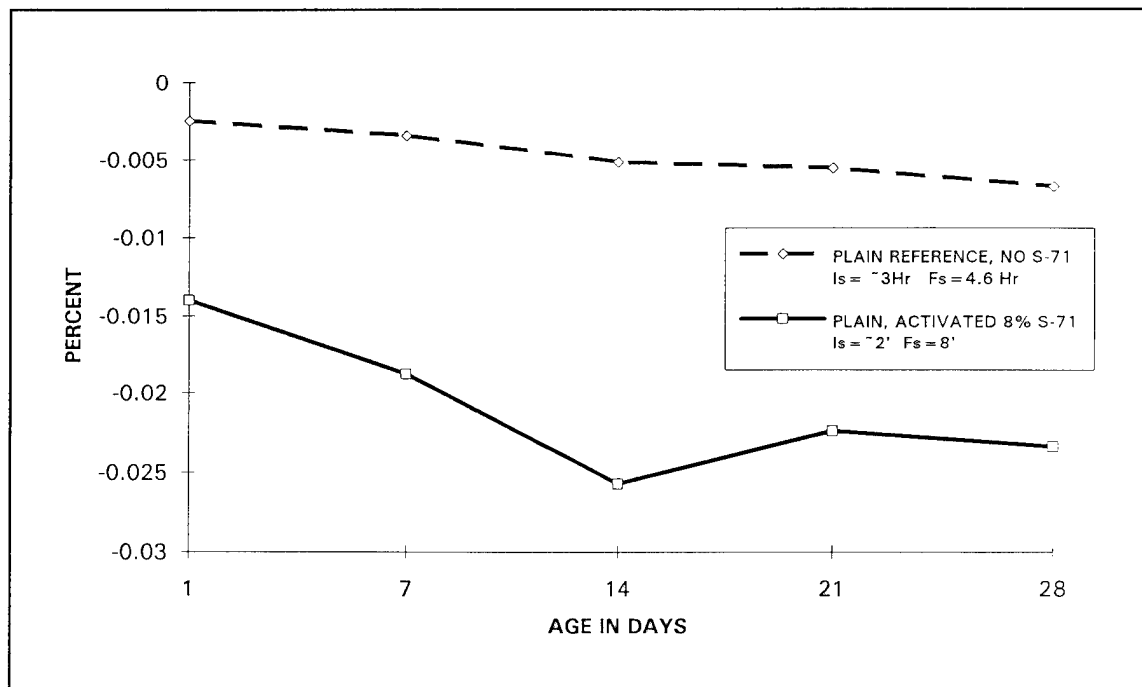
Figure D13. Compressive-strength development of shotcrete containing Type II cement activated at 48 hr with 8-percent S-71 by mass of cement
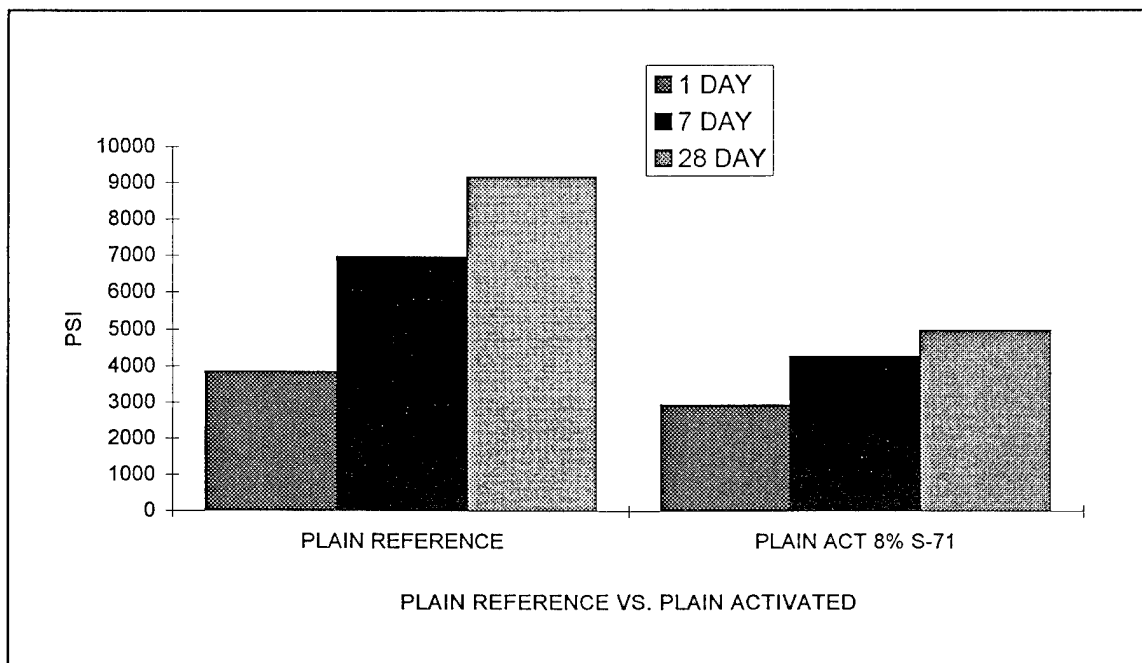
Figure D14. Compressive-strength comparison of plain reference and plain activated shotcrete with 8-percent S-71 by mass of cement
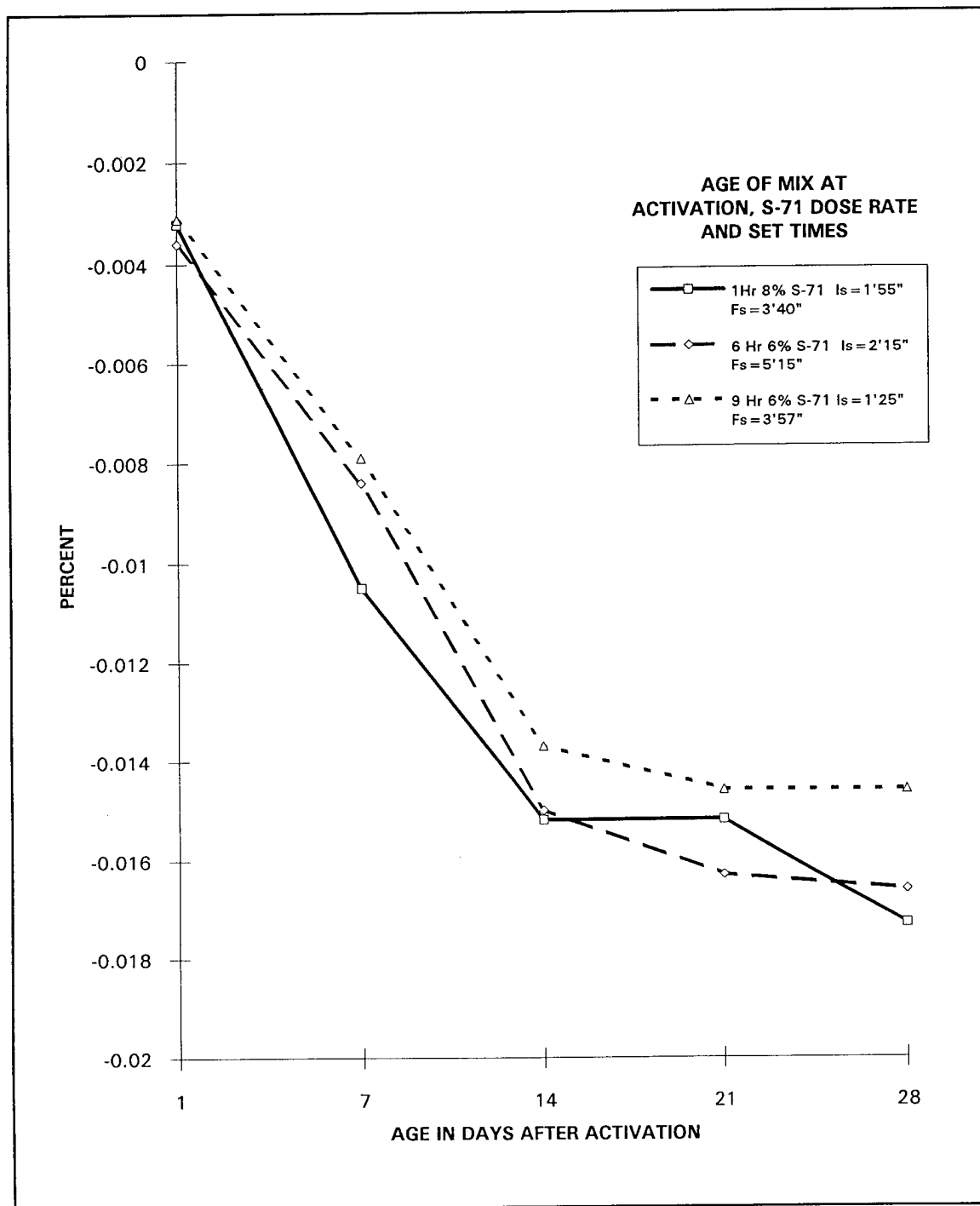
Figure D15. Length-change results of shotcrete treated with 0.6-percent DELVOCRETE Stabilizer by mass of cement

AGE OF MIX AT ACTIVATION, S-71 DOSE RATE AND SET TIMES

- 1 Hr 8% S-71 Is = 1' 55" Fs = 3'40"
- 6 Hr 6% S-71 Is = 2'15" Fs = 5'15"
- 9 Hr 6% S-71 Is = 1'25" Fs = 3'57"

PSI

Time in Hours or Days
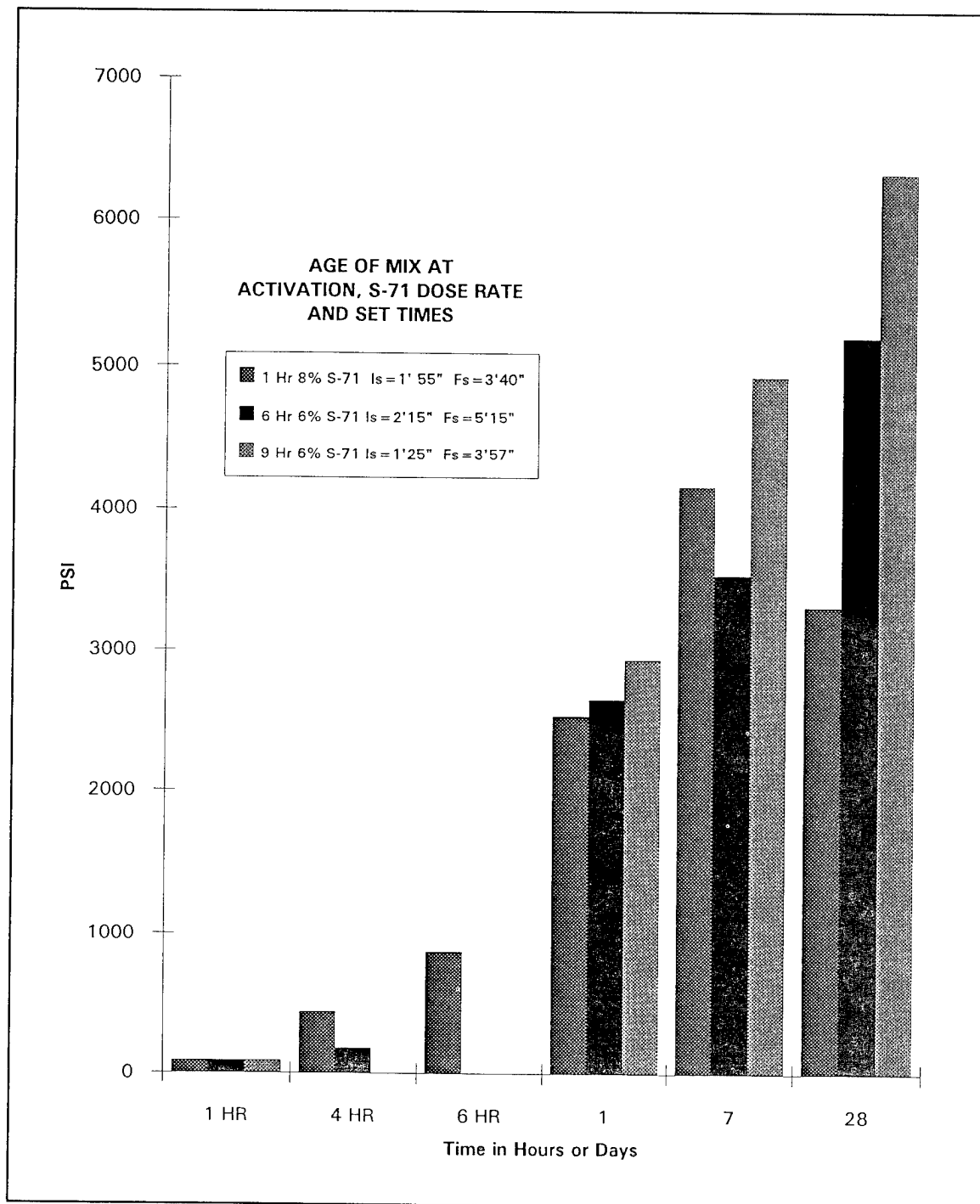
Figure D16. Comparison of compressive-strength results of shotcrete treated with 0.6-percent DELVOCRETE Stabiizer by mass of cement

Appendix D   Compressive-Strength Development of Shotcrete Mixtures Monitored for 28 days
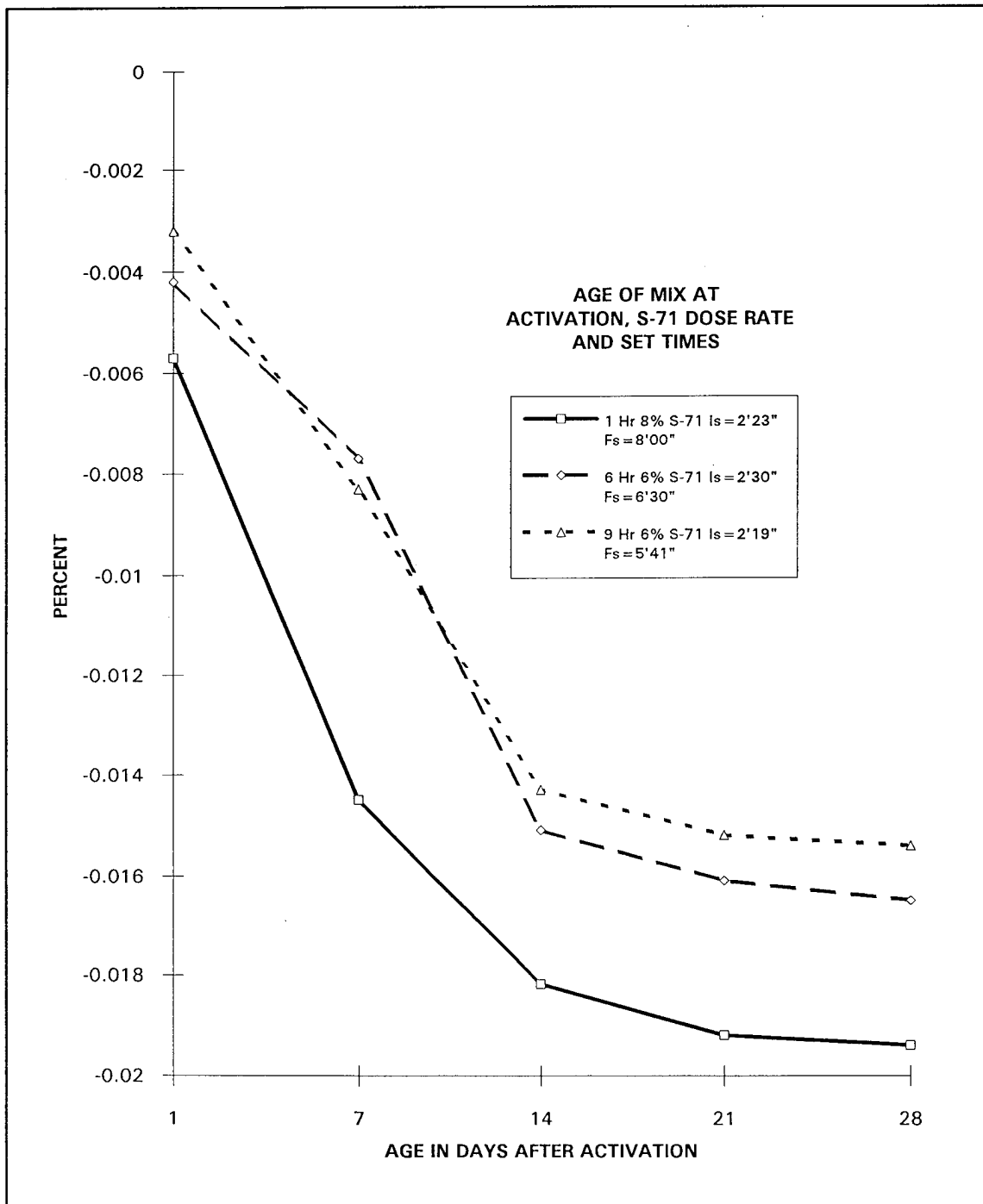
Figure D17. Length-change results of shotcrete treated with DELVOCRETE Stabilizer at 1 percent by mass of cement
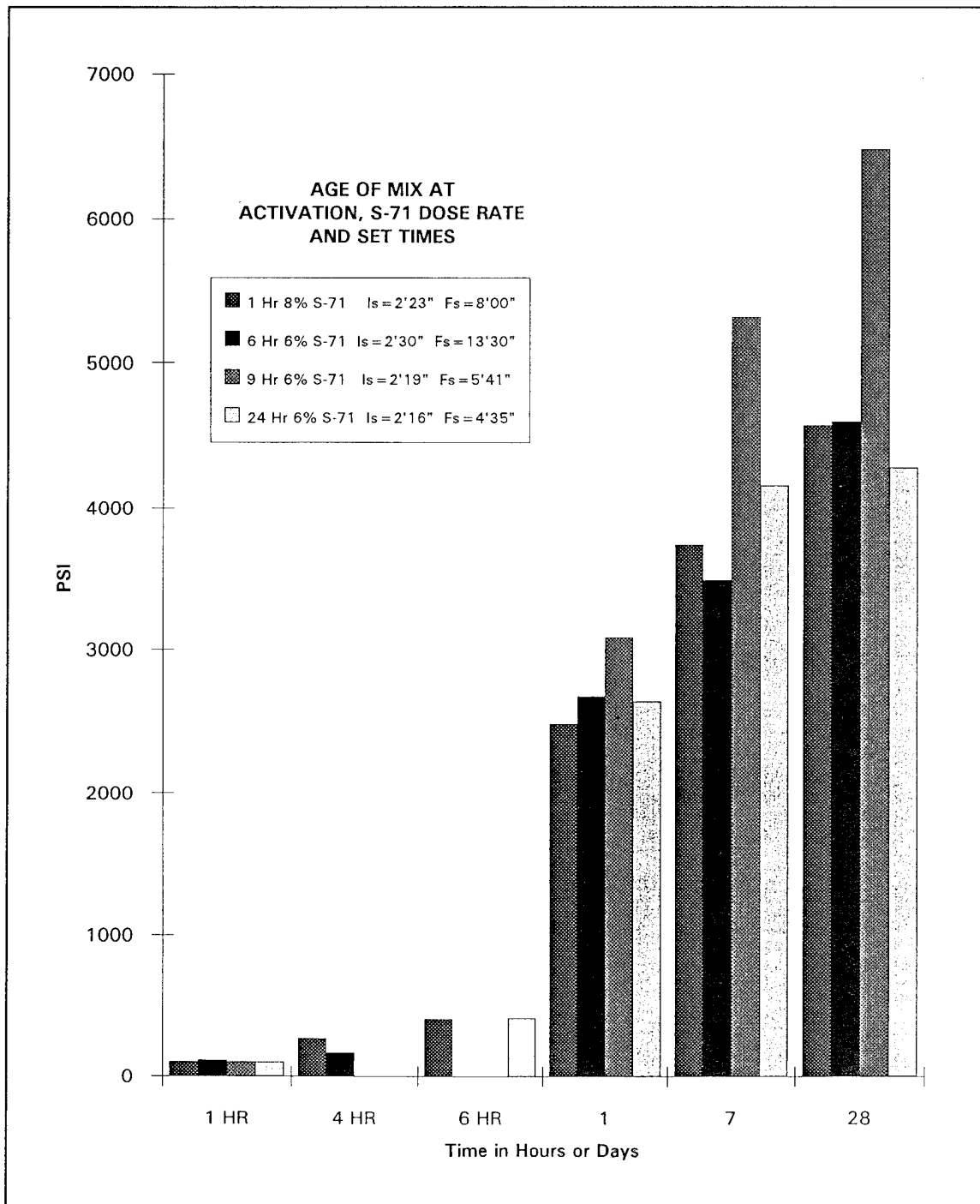
Figure D18. Comparison of compressive-strength results of shotcrete treated with
1-percent DELVOCRETE Stabilizer by mass of cement

Appendix D   Compressive-Strength Development of Shotcrete Mixtures Monitored for 28 days
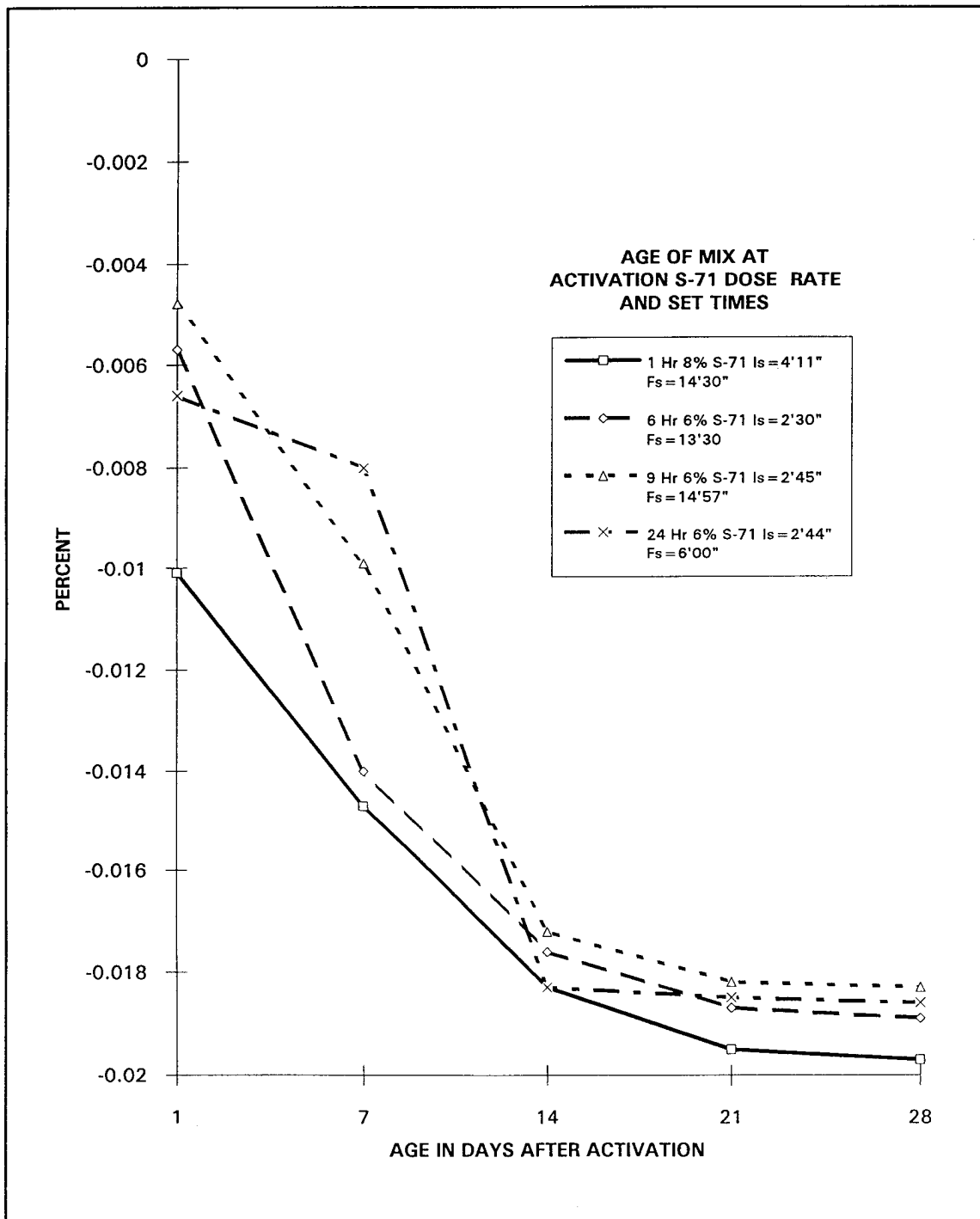
Figure D19. Length-change results of shotcrete treated with 2-percent DELVOCRETE Stabilizer by mass of cement
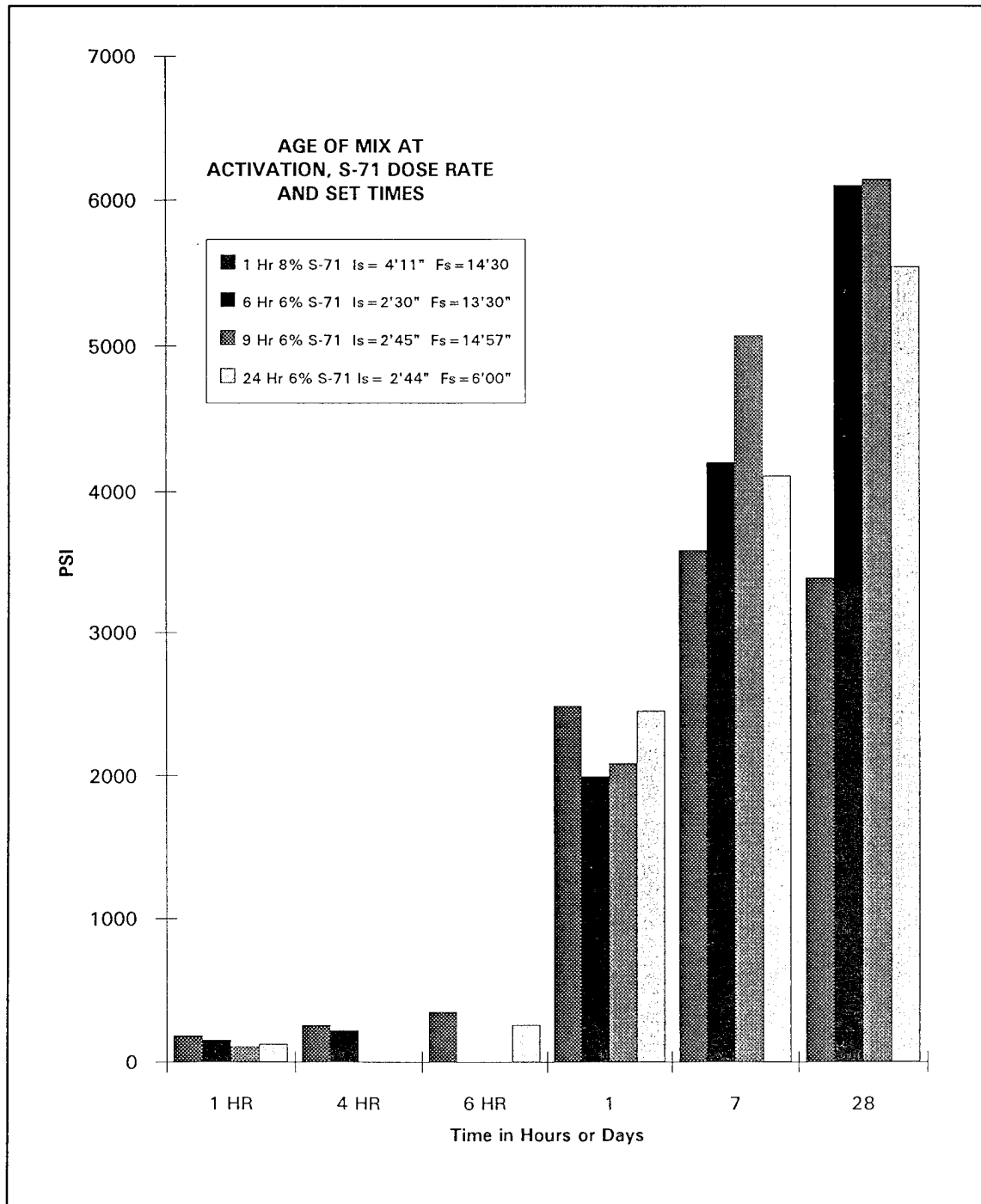
Figure D20. Comparison of compressive-strength results of shotcrete treated with
2-percent DELVOCRETE Stabilizer by mass of cement

Appendix D   Compressive-Strength Development of Shotcrete Mixtures Monitored for 28 days

Appendix E
Use of DELVO for Headerless Paving

In highway paving, at the end of the workday or in the event of an anticipated delay in paving activity, the last 1 to 1-1/2 hr are used to construct a header. A header is a bulkhead constructed at the end of the last concrete placement of the day to provide a formed surface while the concrete hardens. Construction of the header is a time-consuming, laborious procedure that reduces the daily productivity of a paving crew. Prior to the beginning of the next day of paving activity, the header constructed at the end of the previous workday must be disassembled, another time consuming and laborious process that can take another hour of production out of a day of paving. By eliminating the need to construct and subsequently disassemble such structures, the daily productivity of a paving crew would be improved.

One way to eliminate the need of headers would be to stabilize the last paving concrete loads of the day with DELVO Stabilizer for a period of time that would keep the last load of concrete plastic until the next morning when that load could be integrated with a fresh load of concrete to begin the next paving day. The purpose of this portion of the DELVO-CPAR project was to study the feasibility of using DELVO Stabilizer in paving to eliminate the need for constructing headers in routine paving.

Much of the work on headerless paving was completed prior to, and in anticipation of, the formal beginning of the DELVO-CPAR project. Field activity for this portion of the study was anticipated to continue throughout the project, but most of the concept and operational procedures had been worked out by early 1991. Since then, interest in continuing field studies of the use of DELVO Stabilizer in paving has been expressed, but only laboratory studies have taken place. No further field activities have occurred since 1991, and the procedure remains experimental.

Tests to Date

In the summer and fall of 1990, three field tests of headerless paving were run in Colorado. In the two cases where the concept was used in a noncritical portion of a highway construction, the concrete was removed because of perceived problems with the concrete. Shallow cracking was observed in the finished surfaces of the stabilized portions and was subsequently related to the finishing procedures used. A finishing aid, water, had been liberally used to finish the concrete after the paving machine had moved off the stabilized portion of the concrete pavement. This produced a thin layer of high water to cement ratio (w/c) concrete and cement paste adjacent to the finished surface; this layer was soft and had cracked as it dried. Subsequent questions of the appropriate time to cut control joints in the concrete arose and were not answered to the satisfaction of the contractor at the time of these early field tests. The testing of the concept of headerless paving resulted in concerns of cold joints in the concrete slabs, and it was reported that a deep crack observed in the concrete at the first field test was thought to have been the result of a cold joint. No features of cold joints were microscopically observed in the petrographic examination of several concrete cores of the concrete taken from that placement. If a cold joint had developed, the location of the crack may have been effectively controlled by the timing and positioning of the control joints cut later. This was a concern of the contractor in the earliest field tests. These concerns may also have been eliminated by the use of a transitional dose of DELVO Stabilizer as in the second field test or by the selection of the overnight DELVO Stabilizer dosage rate. These are issues that will most likely be addressed when further testing of headerless paving occurs.

Since those early tests, interest in headerless paving has been expressed by several paving contractors, but no field tests have been performed since 1990. In the past 2 years, one contractor has stated continued interest in headerless paving, running laboratory tests, and developing a method that eliminates the need for the transitionally dosed morning concrete. Because of paving schedules and a lack of State approval, the concept has not been used in a field test since late 1990. The contractor has indicated a comfort level with the concept and a willingness to implement headerless paving if State approval is received. In considering the issue of the appropriate timing for the cutting of control joints, studies by the paving contractor have been used to develop a method for judging the time most appropriate to cut joints. If interest by the contractor continues, it is possible that the method of headerless paving will be tested again this year.

It is speculated that the integrity of the bond between loads of the overnight concrete would be similar to that of the bonds between layers of roller-compacted concrete, another feasibility study covered in this CPAR project.

Construction of a Pavement Header

The photographs and commentary that follow are based on the September 1990 test, and the refinement of the procedure occurred since that time. Later work was based on the testing by an interested paving customer in Colorado. To show how the use of DELVO Stabilizer would reduce the complexity of paving, the following is a description of the construction of a night header.

The basic steps involved in the construction of paving headers are follows:

a. In normal paving activity, a header is constructed at the end of a workday or when a delay is anticipated during the placement of concrete. After the paving machine has placed and vibrated the last load of concrete, a header is constructed (Figure E1).

b. A square, straight edge is cut across the pavement width (Figure E2).

c. A wooden bulkhead is placed against the square edge to maintain the shape of the edge. The form is held in position by driving steel rods into the subgrade. In Figure E3, two workers are shown holding the form in position while the rods are driven into the subgrade material.

d. Once the header is in place, it must be measured and aligned to the proper height (Figure E4).

e. When adjustments to the header are completed, the concrete layer behind the form is brought up to the proper level, and the concrete behind the header is consolidated. Reinforcement rods are then inserted into the form through holes in the form. These bars are partially driven into the concrete, tying the concrete behind the header to the header. These bars extend beyond the header and will tie the first load of concrete the following morning to the last load of concrete placed the previous day (Figure E5).

f. The concrete behind the header is finished, and the surfaces are protected until the next morning (Figure E6).

Headerless Paving Procedure With DELVO Stabilizer

The headerless paving technique is proposed as an alternative method to the daily construction of a conventional header. By stabilizing the last two loads of pavement concrete at the end of the day, the last load of concrete will

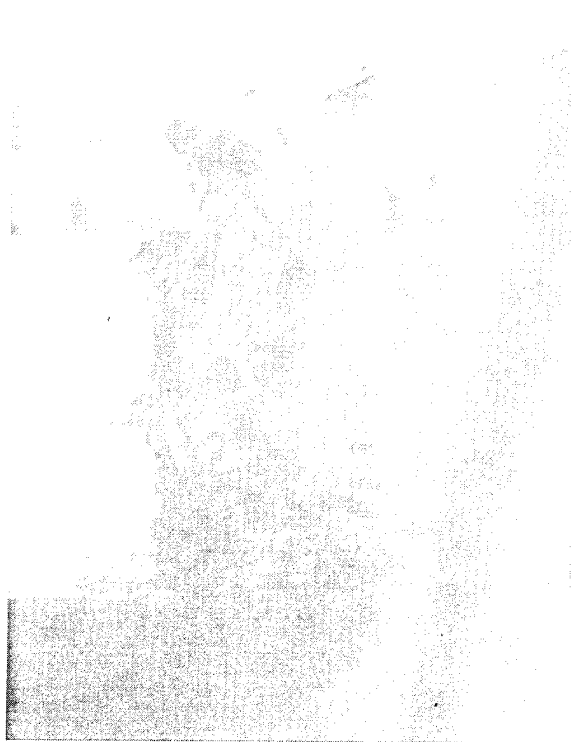Figure E1. The last concrete load of the day is placed

Figure E2. A square, straight edge is cut
across the pavement width

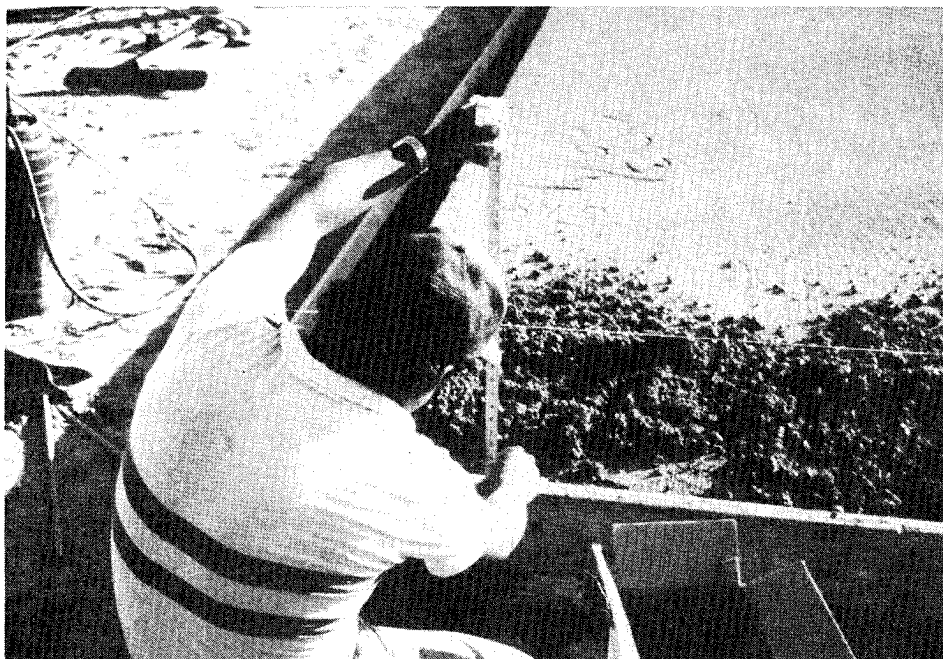Figure E3. The wooden bulkhead is placed against the cut pavement

Figure E4. The bulkhead is aligned to the proper height

Figure E5. Concrete level is aligned behind
the bulkhead, and reinforcement
is inserted into the form

Figure E6. The concrete behind the header is finished and protected until the next morning

remain plastic for a known period of time, and the need for the construction of a header may be eliminated. This saves time and labor and increases daily production of a paving crew. After the paving machine has placed most of the last load of concrete, the DELVO Stabilizing sequence is as follows:

a. First, a transitionally dosed load of concrete is placed immediately after the untreated concrete. This transitional dosage will provide a more gradual difference in the times of setting between the untreated concrete and the concrete dosed with the full overnight DELVO Stabilizer dosage. By eliminating dramatic differences in time of setting between concrete loads, the potential for the development of cold joints is reduced or eliminated. The load of concrete with the transitional DELVO Stabilizer dosage should be large enough to cover the complete pavement width. Next, the full overnight dosage of DELVO Stabilized concrete is batched and placed immediately after the transitional load of concrete. The overnight load should cover the entire width of the pavement and be of sufficient length to allow the paving machine back onto the pavement the next morning to begin where the overnight concrete ended (Figure E7.)

b. A worker wets burlap that covers the stabilized area which where the header would have been constructed (Figure E8.)
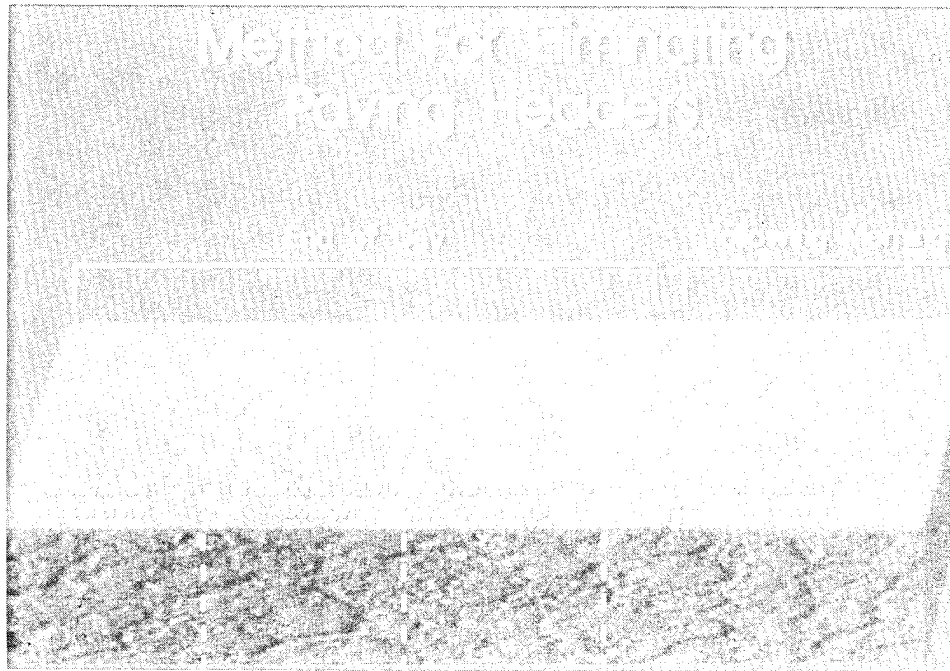
Figure E7. Schematic diagram of headerless paving

Figure E8. A worker wets burlap over DELVO-stabilized area

c. The burlap is then covered with plastic, and it is recommended that the concrete be covered with insulating blankets since the concrete will cool as temperatures go down in the night. If substantial heat is lost during the night, the time of setting of the concrete will be prolonged with respect to warmer conditions. Swings in temperature will make the prediction of time of setting less accurate. The use of insulating blankets will maintain concrete temperatures throughout the night, providing more uniform setting performance (Figure E9).

d. The next morning, the coverings are removed to expose the plastic concrete from the previous day and fresh concrete is placed along the front of the overnight concrete; the vibrators of the paving machine penetrate the overnight stabilized concrete, blend it with the first load of fresh, untreated concrete of the day, and continue paving without having constructed a header (Figure E10).

e. Because this was a test, the crew constructed a header the previous day as a safety measure. The next morning, the concrete had not set, and the reinforcement bar could be moved in the header (Figure E11).

f. The first load of the day is placed in front of the overnight, DELVO Stabilized concrete (Figure E12).

g. A front-end loader is used to place the fresh concrete on top of the stabilized concrete of the previous day's work where the two loads meet (Figure E13).

h. The paving machine then vibrates the two loads together so that some blending occurs (Figure E14).

i. From that point on, the paving machine can continue placing fresh concrete where it had stopped at the end of the previous paving day (Figure E15)

j. Figure E16 shows an alternate plan for the following morning if cold joints are of concern. It is expected that this will not be necessary if the timing of the initial time of setting of the overnight load and the first load of the day are compatible and well intermixed the following morning. No evidence of a cold joint was observed in cores taken of the concrete from this placement, and no deep cracking was detected in the concrete after the concrete had hardened.

Use of Information

Several paving contractors have expressed interest in the use of DELVO Stabilizer to eliminate the need for construction of night headers at the end of the paving workday. These potential customers are aware of the possibilities of the use of the method, but because of the novelty of the method, State
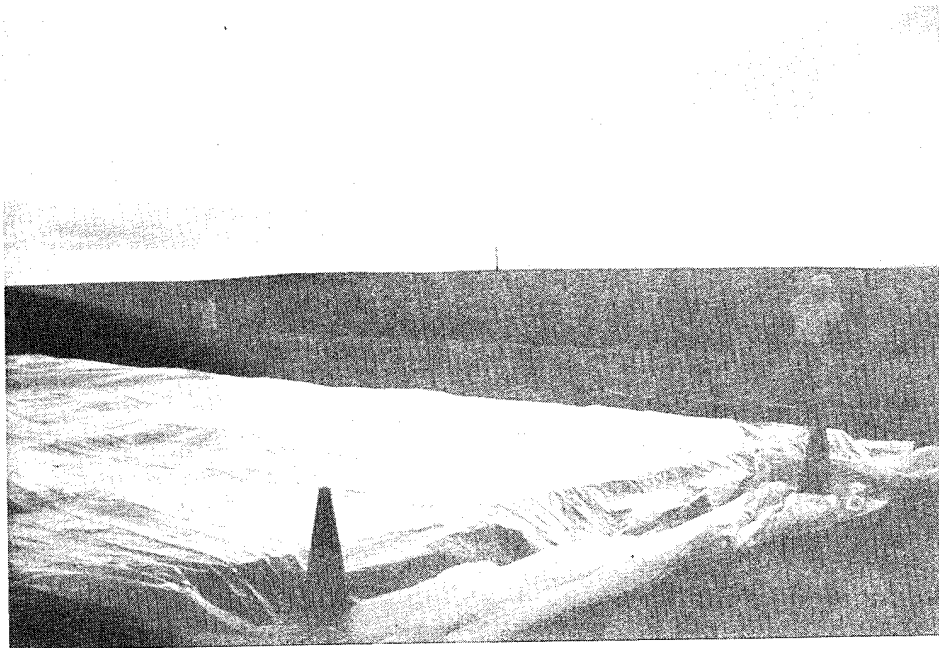
Figure E9. Plastic sheets are placed over the DELVO-stabilized area
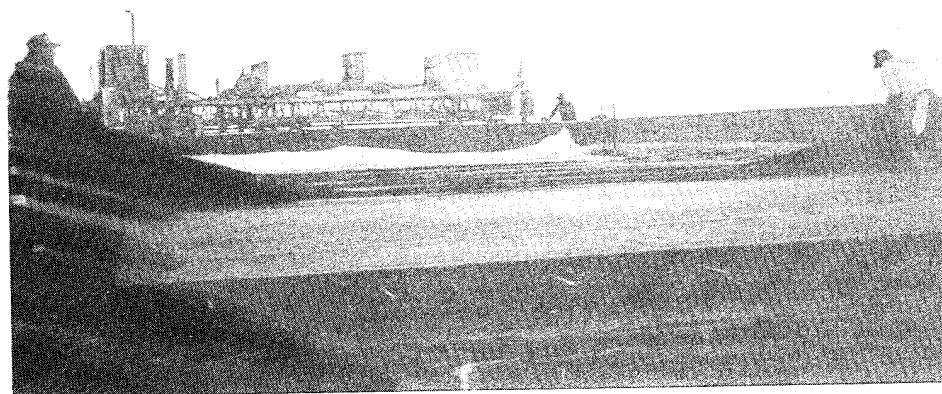

Figure E10. Insulation, plastic sheets, and burlap are removed the next morning

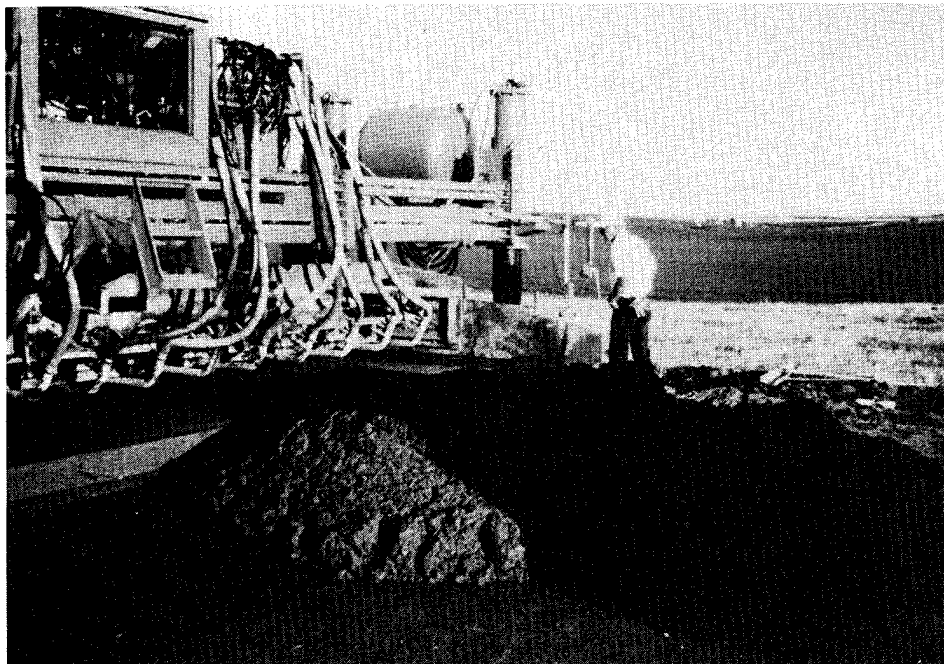Figure E11.   The next morning the reinforcement bar can be moved in the header

Figure E12.   The first load of the morning is placed in front of the overnight DELVO-stabilized load
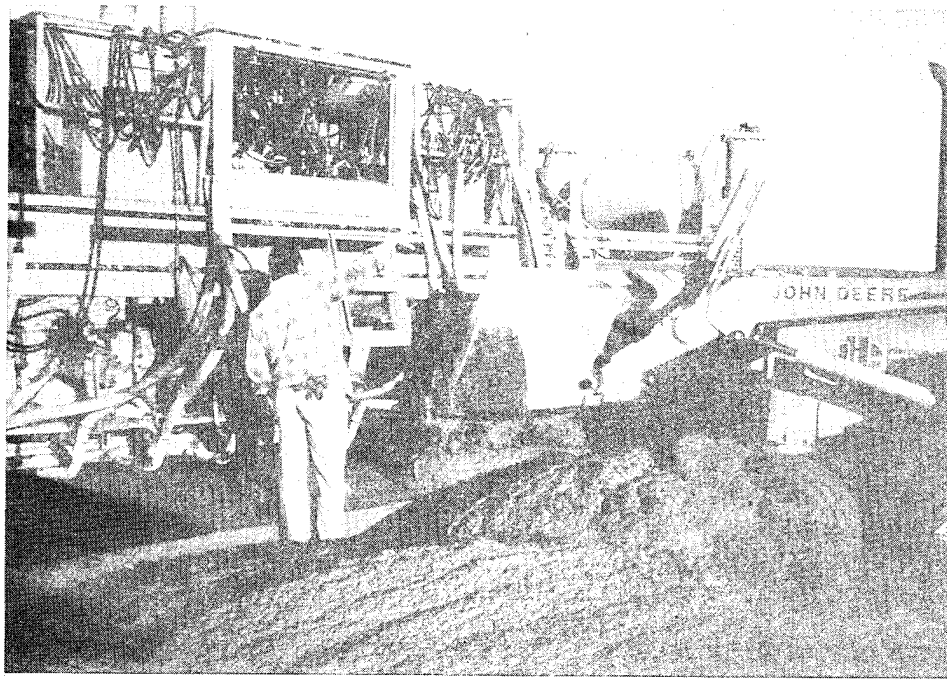
Figure E13. A front end loader places fresh concrete on top of the
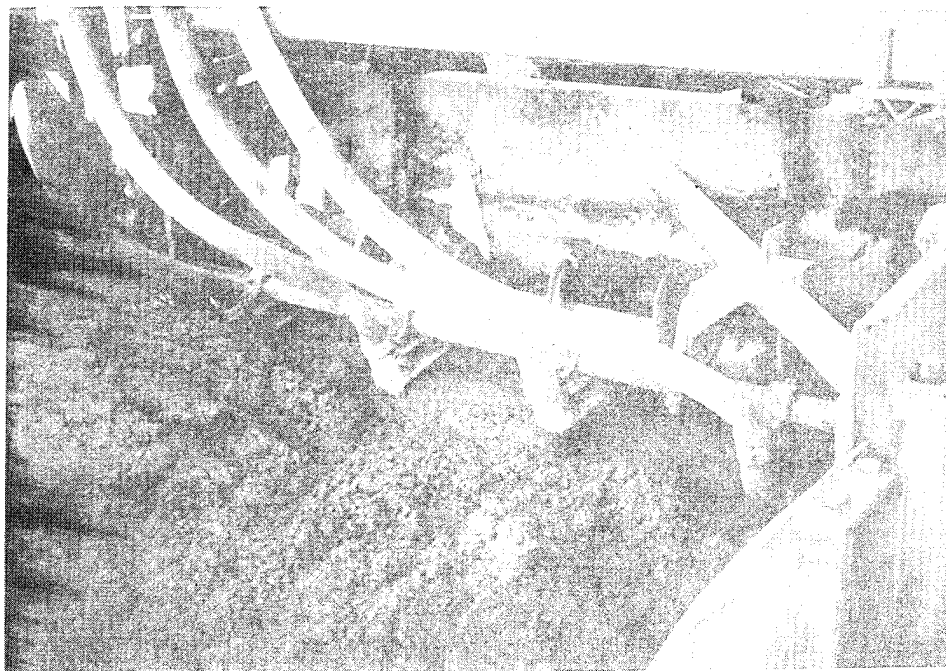overnight DELVO-stabilized concrete
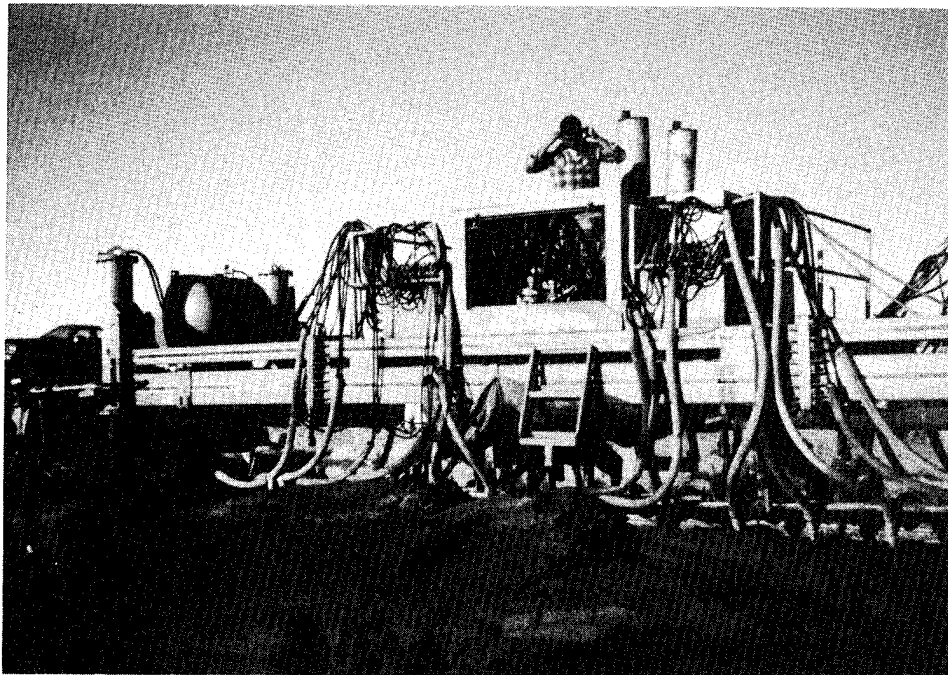

Figure E14. The paving machine vibrates and integrates the two loads

Figure E15. The paving machine can proceed, placing fresh concrete where it had stopped the previous day
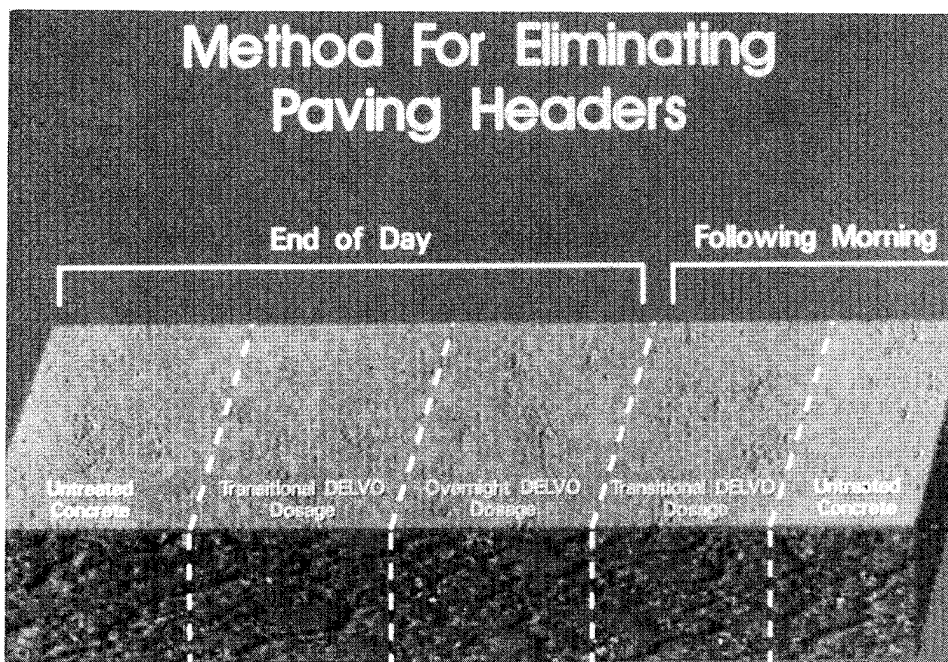
Figure E16. An alternative method for the next morning if cold joints are of concern

agencies have not recognized the method of routine use of DELVO Stabilizer for the elimination of paving headers. The work done to date has produced a method which should work in practice. Interested paving customers will be made aware of the existence of the method. Refinement of the method may require more testing of the concept in the field to address the concerns regarding the development of cold joints. The use of protection procedures for placed concrete and transitionally dosed concrete loads, along with fully dosed, overnight concrete loads have been tested and were shown to prevent or reduce the potential for the development of cold joints. DELVO Stabilizer dosage rates for paving concrete are expected to resemble the charts used in the long-haul procedures for pavement mixtures that must be dosed for periods of 18 hr for the overnight stabilization.

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13. ABSTRACT *(Maximum 200 words)*

Fresh concrete is a perishable product that must normally be transported, placed, consolidated, and finished within a relatively short time if the hardened concrete is to develop the desired engineering properties and perform as designed. As a result of these concrete discharge-time limitations, concrete producers often attempt to extend the concrete working time by introducing chemical admixtures into the concrete either at the time of batching or upon arrival at the work site. In cases where fresh concrete has exceeded the specified delivery times or when more concrete is ordered than can be used at a project, the producer must deal with disposing of it. Both waste fresh concrete and mixer wash water are classified as hazardous waste, and the disposal of these materials is highly regulated.

The commercially available admixture system DELVO has been developed to enable the concrete producer to tailor the working time of fresh concrete to that needed for particular applications and ambient conditions and to deal with the problems of waste fresh concrete and wash-water disposal. An investigation was conducted to verify the performance test results for concrete containing the DELVO Stabilizer and Activator and to develop new applications for DELVO technology

(Continued)

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in order to reduce concrete mixture costs, increase concrete construction productivity, and reduce the adverse environmental impact associated with the disposal of waste fresh concrete.

The investigation focused attention on an evaluation of DELVO Stabilizer and Activator for standard ready-mixed concrete applications, including long-haul, same-day, and overnight stabilization. Tests were conducted on fresh and hardened concrete and included temperature, slump, air content, time of setting, compressive strength, flexural strength, resistance to rapid freezing and thawing, length change, rapid chloride-ion penetration, and parameters of air-void system. Also investigated was the feasibility of using DELVO Stabilizer to reduce peak temperatures in lean mass concrete and thereby minimize the cracking potential caused by the generation of excessive tensile stresses resulting from differential cooling within the structure. Tests conducted included adiabatic temperature rise, shrinkage, creep, and modulus of elasticity. An abbreviated investigation was made to assess the feasibility of using DELVO Stabilizer in roller-compacted concrete.

Simplification procedures were developed for determining DELVO Stabilizer dosage rates for use in same-day and overnight stabilization of conventional concrete. The feasibility of using DELVO to minimize construction joints in concrete paving and stabilizing shotcrete mixtures was also examined.